



## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> :  B01J 13/02, 13/14, 13/16, 13/18, B32B 9/02, 19/00, 19/02, 27/00		A1	(11) International Publication Number: <b>WO 99/12640</b>  (43) International Publication Date: 18 March 1999 (18.03.99)
<p>(21) International Application Number: PCT/US98/18639</p> <p>(22) International Filing Date: 8 September 1998 (08.09.98)</p> <p>(30) Priority Data: 60/058,309 9 September 1997 (09.09.97) US</p> <p>(71) Applicant (for all designated States except US): SELECT RELEASE, L.C. [US/US]; 15310 Fox Briar Lane, Midlothian, VA 23112 (US).</p> <p>(72) Inventor; and</p> <p>(75) Inventor/Applicant (for US only): ANDERSON, David, M. [US/US]; 103 Croatan Circle, Cary, NC 27513 (US).</p> <p>(74) Agent: MCCONOUGHEY, David, M.; Wyatt, Gerber, Meller, &amp; O'Rourke, L.L.P., 6th floor, 99 Park Avenue, New York, NY 10016-1501 (US).</p>		<p>(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).</p> <p><b>Published</b>  <i>With international search report.  Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i></p>	
<p>(54) Title: COATED PARTICLES, METHODS OF MAKING AND USING</p> <p>(57) Abstract</p> <p>A coated particle is disclosed that comprises an internal core comprising a matrix and an exterior coating. The matrix consists essentially of at least one nanostructured liquid phase, or at least one nanostructured liquid crystalline phase or a combination of the two and the exterior coating comprising a nonlamellar crystalline material. Methods of making and methods of using the coated particle are disclosed.</p>			

**FOR THE PURPOSES OF INFORMATION ONLY**

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakhstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

## COATED PARTICLES, METHODS OF MAKING AND USING

### BACKGROUND OF THE INVENTION

#### FIELD OF THE INVENTION

The present invention relates to coated particles and to methods of making and using them. These coated particles have application in the release of one or more materials into selected environments. the absorption of one or more materials from selected environments and the adsorption of one or more materials from selected environments.

#### RELATED ART

Two particle technologies—polymer-coated particles and liposomes—are of general interest.

Polymer-coated particles exhibit several limitations. as the flattened and diffuse response of their polymer coatings to chemical and physical triggers indicates. This is due to two factors. First. the high molecular weight of polymers reduces their diffusion coefficients and their kinetics of solubilization. Second. the neighboring group effect broadens the curves representing the chemical responses to triggers such as. *inter alia*. pH. salinity. oxidation and reduction, ionization. etc. (The neighboring group effect indicates that chemical changes in one monomeric unit of a polymer significantly alter the parameters governing chemical transitions in each of the neighboring monomeric units.) Further. most polymers are collections of chemical species of broadened molecular weight distribution. In addition. for a given application of the polymer-coated particle only a limited number of suitable polymers are frequently available. This is due to a number of factors: regulatory issues: the coating processes often entail harsh chemical and/or physical conditions. such as solvents. free radicals. elevated temperatures. dessication or drying, and/or macroscopic shearing forces needed to form the particles: the mechanical and thermal stabilities of the polymeric coatings in industrial applications are limited and further there is the adverse environmental impact of the large scale application of polymer-coated particles. such as in agricultural use.

Liposomes also exhibit a number of limitations. Among these are their physical and chemical instabilities. The release of a material disposed within the liposome is usually dependent on the destabilization of the structure of the liposome. In particular. the absence of porosity precludes the pore-controlled release of such materials. The dual requirements of 1)

physical stability of the liposome until release is desired on the one hand and 2) release of materials by bilayer destabilization when release is desired on the other are problematic. (The term liposomes is frequently interchanged with the term vesicles and is usually reserved for vesicles of glycerophospholipids or other natural lipids. Vesicles are self-supported closed bilayer assemblies of several thousand lipid molecules (amphiphiles) that enclose an aqueous interior volume. The lipid bilayer is a two-dimensional fluid composed of lipids with their hydrophilic head groups exposed to the aqueous solution and their hydrophobic tails aggregated to exclude water. The bilayer structure is highly ordered yet dynamic because of the rapid lateral motion of the lipids within the plane of each half of the bilayer.) See O'Brien, D.F. and 5 Ramaswami, V. (1989) in Mark-Bikales-Overberger-Menges Encyclopedia of Polymer Science and Engineering, Vol. 17, 2<sup>nd</sup> Ed., John Wiley & Sons, Inc., p. 108.

#### BRIEF SUMMARY OF THE INVENTION

It is an object of the invention to provide coated particles that are suitable for solubilizing or containing a wide variety of materials, including materials sensitive to physical, chemical or 15 biological deterioration.

It is an object of the invention to provide coated particles that release one or more materials disposed within a matrix in their internal cores without requiring the destabilization of that matrix.

It is an object of the invention to provide coated particles that sharply initiate the release 20 or absorption of one or more materials to or from a selected environment in response to one or more physical or chemical triggers.

It is an object of the invention to provide coated particles that provide a wide variety of coated particle systems that can be tailored to the particular physical, chemical and biological requirements of their contemplated use, such as mechanical and thermal stability in industrial 25 applications of the coated particles or freedom from adverse environmental impact in large scale application of the coated particles in agricultural use.

It is an object of the invention to provide coated particles that provide, if desired, a porous coating that permits pore-controlled release of materials disposed within them or pore-controlled absorption of materials disposed without them.

30 It is a still further object of the invention to provide coated particles that can be made by a simple process, including, preferably, without entailing harsh physical and/or chemical

conditions.

The foregoing and other objects are provided by a coated particle that comprises an internal core comprising a matrix and an exterior coating. The matrix consists essentially of at least one nanostructured liquid phase, or at least one nanostructured liquid crystalline phase or a combination of the two and the exterior coating comprises a nonlamellar crystalline material.

In a preferred embodiment, the coated particle may be made by

1. providing a volume of the matrix that includes at least one chemical species having a moiety capable of forming a nonlamellar crystalline material upon reaction with a second moiety and
- 10 2. contacting the volume with a fluid containing at least one chemical species having the second moiety under nonlamellar crystalline material-forming conditions so as to react the first moiety with the second moiety and contemporaneously subdividing the volume into particles by the application of energy to the volume.

Alternatively, the coated particle can be made by

- 15 1. providing a volume of the matrix that includes a material in solution in it that is capable of forming a nonlamellar crystalline material that is insoluble in the matrix and
2. causing the aforesaid material to become insoluble in the matrix and contemporaneously subdividing the volume into particles by the application of energy to the volume.

Or, alternatively, a combination of these two methods can be applied.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a graphic representation, in vertical section, illustrating a coated particle of the present invention comprising an internal core comprising a 2 by 2 by 2 unit cell matrix and an exterior coating;

Fig. 2 is a graphic representation, in section, illustrating a coated particle of the present invention;

Fig. 3 is a scanning electron microscope micrograph of coated particles of the present invention;

30 Fig. 4 is a scanning electron microscope micrograph of other coated particles of the present invention;

**Fig. 5** is a graph of the measured volume-weighted cumulative particle size distribution for coated particles of the present invention on a volume-weighted particle diameter versus cumulative particle size basis;

5 **Fig. 6** is a graph of measured small-angle X-ray scattering intensity versus wave vector  $q$  of coated particles of the present invention;

**Fig. 7** is a graph of detector counts versus elution time in minutes for a control using high pressure liquid chromatography; and

**Fig. 8** is a graph of detector counts versus elution time in minutes for coated particles of the present invention using high pressure liquid chromatography.

## 10 DESCRIPTION OF THE PREFERRED EMBODIMENTS

As illustrated in Figs. 1 and 2, a coated particle **1** of the present invention comprises an internal core **10** and a coating **20** exterior to it (hereinafter "exterior coating **20**."). The internal core **10** comprises a matrix consisting essentially of a nanostructured material selected from the group consisting of

15 a. at least one nanostructured liquid phase,  
b. at least one nanostructured liquid crystalline phase and  
c. a combination of  
i. at least one nanostructured liquid phase and  
ii. at least one nanostructured liquid crystalline phase.

20 The liquid phase material and the liquid crystalline phase material may either contain solvent (lyotropic) or not contain solvent (thermotropic.) The exterior coating **20** comprises a nonlamellar crystalline material. The term "exterior coating" as used herein is intended to indicate that the coating **20** is exterior to the internal core **10** and is not intended to be limited to meaning that the exterior coating **20** is the most exterior coating of the coated particle **1**.

25 Nanostructured liquid phase and nanostructured liquid crystalline phase possess unique properties that are not only important in making possible the easy production of particles according to the present invention, but also yield highly desirable solubilization, stability, and presentation properties and other capabilities in the final coated particles of the present invention.

30 As for the exterior coating **20**, non-lamellar crystalline structures which exhibit bonding and/or packing rigidity that extends in all three dimensions are strongly preferred in the present invention over lamellar (layered) materials due to the well-known physical and chemical

instabilities of lamellar crystalline structures, as exemplified by, for example, (a) the instability (even when acquiescent) of emulsions which have droplets coated with lamellar liquid crystalline layers, (b) the chemical instability upon removal of guest molecules in lamellar Werner complexes, and (c) the dramatically inferior hardness and shear modulus for graphite as compared with diamond.

5 Coated particles 1 of the present invention may be from 0.1 micron to 30 microns in mean caliper diameter, and preferably from about 0.2 micron to about 5 microns in mean caliper diameter. The coated particle 1 may also be provided with a stabilizing layer on its exterior, i.e., outside the exterior coating 20, as desired, such as a polyelectrolyte or surfactant monolayer to prevent agglomeration of coated particles 1.

10 The coated particles 1 of the present invention have application in a variety of modalities of use. The coated particle 1 may, upon release of the exterior coating 20, absorb one or more materials from a selected environment, adsorb one or more materials from a selected environment or release one or more materials, such as active agents, disposed in the matrix into a 15 selected environment. Alternatively, certain exterior coatings possessing porosity, such as inclusion compounds and zeolites, do not require release in order to effect the absorption or release of a material of interest into or out of the matrix, and in some such cases very high selectivity can be obtained by the use of properly tuned pore characteristics. In cases where the 20 particles are used to adsorb a compound or compounds of interest, neither porosity nor release of the exterior coating 20 are required, but porosity can provide for a very large increase in adsorption capacity by allowing the adsorbed material to diffuse into the matrix, making the adsorption sites in the exterior coating 20 available to adsorb new material. In a preferred embodiment, an additional material, such as an active agent, may be disposed within the matrix for release into a selected environment.

25 The matrix is

- a. thermodynamically stable
- b. nanostructured and
- c. a liquid phase or liquid crystalline phase or a combination thereof.

30 **Nanostructured:** The terms "nanostructure" or "nanostructured" as used herein in the context of the structure of a material refer to materials the building blocks of which have a size that is on the order of nanometers ( $10^{-9}$  meter) or tens of nanometers ( $10 \times 10^{-9}$  meter.) Generally speaking,

any material that contains domains or particles 1 to 100 nm (nanometers) across, or layers or filaments of that thickness, can be considered a nanostructured material. (See also Dagani, R., "Nanostructured Materials Promise to Advance Range of Technologies," November 23, 1992 C&E News 18 (1992).) The term is meant to exclude so-called "ceramic glasses" which are 5 crystalline materials in which the crystallite size is so small that one may not observe peaks in wide-angle x-ray diffraction and which some physicists may refer to as nanostructured materials; the nanostructured liquid and liquid crystalline phases that are defined herein are characterized by nanoscale domains which are clearly distinguished from neighboring domains by large differences in local chemical composition, and do not include materials in which neighboring 10 domains have essentially the same local chemical composition and differ only in lattice orientation. Thus, by the term 'domain' as used herein it is meant a spatial region which is characterized by a particular chemical makeup, which is clearly distinguishable from that of neighboring domains: often such a domain is hydrophilic (hydrophobic) which contrasts with the hydrophobicity (hydrophilicity) of neighboring domains; in the context of this invention the 15 characteristic size of these domains is in the nanometer range. (The term 'microdomain' is often used to indicate domains whose size range is micron or nanometer scale.)

Nanostructured liquid phases and liquid crystalline phases, which provide the matrix of the internal cores 10 of the coated particles 1 in the present invention, possess unique collections 20 of properties that are not only crucial in making possible the production of particles of the present invention, but also yield highly desirable solubilization, stability, and presentation properties and capabilities in the final coated particles. As discussed in more detail below in the discussion of particle production processes, in order that a material provide for ready dispersibility with one of the processes described herein, it is desirable for the material to be of very low solubility in water (otherwise it will tend to dissolve during the dispersing process, 25 limiting dispersibility), yet, at the same time it should contain water — both for the purpose of solubilizing water-soluble reactants used in dispersing and for making possible the solubilization of a large range of active compounds.

In particular, for solubilization of hydrophilic (especially charged) and amphiphilic 30 compounds, and for the maintenance of not only solubilization but also proper conformation and activity of sensitive compounds of biological origin such as proteins, the interior matrix should contain substantial concentrations of water, or other polar solvent. In terms of establishing versatility in coating selection, a great many (perhaps a majority) of the compounds listed as

useful coatings in the present invention require reactants that are soluble only in polar solvents. Furthermore, the use of organic solvents for solubilization is in most cases inconsistent with biological compounds such as proteins, and in any case is highly disfavored from regulatory, environmental, and health considerations. These two requirements of water-insolubility and 5 solubilization of water-soluble compounds are, of course, working in opposite directions, and are difficult to resolve in a single, inexpensive, and safe material.

Very effective systems for satisfying such solubilization requirements are provided by lipid - water systems, in which microdomains are present which are very high in water content, and simultaneously hydrophobic domains are in very close contact with the aqueous domains. 10 The presence of aqueous domains circumvents precipitation tendencies encountered in systems where water structure is interrupted by the presence of high loadings of co-solvents or co-solutes, as, for example, in concentrated aqueous polymer solutions. At the same time the proximity of hydrophobic domains provides for effective solubilization of amphiphilic compounds (and hydrophobic as well).

15 Nanostructured liquid and liquid crystalline phases are synthetic or semisynthetic materials which adopt these solubilization characteristics, and provide pure, well-characterized, easily produced, inexpensive matrices that also have the following desirable properties:

- a) versatility in chemical systems forming nanostructured liquid phases and nanostructured liquid crystalline phases, ranging from biological lipids that are ideal for 20 biomolecules, to hardy fluorosurfactants, to glycolipids that bind bacteria, to surfactants with ionic or reactive groups, etc.: this provides for applicability over a wide range of conditions and uses;
- b) the unsurpassed ability of nanostructured liquid phases and nanostructured liquid crystalline phases to: i) solubilize a wide range of active compounds including many 25 traditionally difficult compounds such as Paclitaxel and biopharmaceuticals, circumventing the need for toxic and increasingly regulated organic solvents; ii) achieve high concentrations of actives with uncompromised stability; and iii) provide the biochemical environment that preserves their structure and function;
- c) true thermodynamic stability, which ensures against instabilities common with other 30 vehicles, such as precipitation of active agents, breaking of emulsions, vesicle fusion, etc.; and,
- d) the presence of a porespace with preselectable pore size in the nanometer range,

facilitating further control of the release kinetics even after triggered release of the coating, particularly in the release of proteins and other biomacromolecules.

The desired properties of the nanostructured material of the internal core **10** derive from several related concepts regarding materials that can be described with respect to surfactants by 5 use of the terms "polar," "apolar," "amphiphile," "surfactant" and the "polar-apolar interface," and analogously with respect to block copolymer systems, as described below.

**Polar:** polar compounds (such as water) and polar moieties (such as the charged head groups on ionic surfactants or on lipids) are water-loving, or hydrophilic; "polar" and "hydrophilic" in the context of the present invention are essentially synonymous. In terms of 10 solvents, water is not the only polar solvent. Others of importance in the context of the present invention are: glycerol, ethylene glycol, formamide, N-methyl formamide, dimethylformamide, ethylammonium nitrate, and polyethylene glycol. Note that one of these (polyethylene glycol) is actually a polymer, thereby illustrating the range of possibilities. At sufficiently low molecular weights, polyethylene glycol (PEG) is a liquid, and although PEG has not been extensively 15 studied as a polar solvent in combination with surfactants, it has been found that PEG does form nanostructured liquid phases and liquid crystalline phases in combination with, for example, surfactants such as BRIJ-type surfactants, which are nonionic surfactants with PEG head groups ether-linked to alkane chains. More generally, in terms of polar groups in hydrophilic and amphiphilic molecules (including but not limited to polar solvents and surfactants), a number of 20 polar groups are tabulated below, in the discussion of which polar groups are operative as surfactant head groups and which are not.

**Apolar:** Apolar (or hydrophobic, or alternatively "lipophilic") compounds include not only the paraffinic / hydrocarbon / alkane chains of surfactants, but also modifications of them, such as perfluorinated alkanes, as well as other hydrophobic groups, such as the fused-ring 25 structure in cholic acid as found in bile salt surfactants, or phenyl groups as form a portion of the apolar group in TRITON-type surfactants, and oligomer and polymer chains that run the gamut from polyethylene (which represents a long alkane chain) to hydrophobic polymers, such as hydrophobic polypeptide chains in novel peptide-based surfactants that have been investigated. A listing of some apolar groups and compounds is given below, in the discussion of useful 30 components of the nanostructured phase interior.

5 **Amphiphile:** an amphiphile can be defined as a compound that contains both a hydrophilic and a lipophilic group. *See* D. H. Everett, Pure and Applied Chemistry, vol. 31, no. 6, p. 611, 1972. It is important to note that not every amphiphile is a surfactant. For example, butanol is an amphiphile, since the butyl group is lipophilic and the hydroxyl group hydrophilic, but it is not a surfactant since it does not satisfy the definition, given below. There exist a great many amphiphilic molecules possessing functional groups which are highly polar and hydrated to a measurable degree, yet which fail to display surfactant behavior. *See* R. Laughlin, Advances in liquid crystals, vol. 3, p. 41, 1978.

10 **Surfactant:** A surfactant is an amphiphile that possesses two additional properties. First, it significantly modifies the interfacial physics of the aqueous phase (at not only the air-water but also the oil-water and solid-water interfaces) at unusually low concentrations compared to nonsurfactants. Second, surfactant molecules associate reversibly with each other (and with numerous other molecules) to a highly exaggerated degree to form thermodynamically stable, 15 macroscopically one-phase, solutions of aggregates or micelles. Micelles are typically composed of many surfactant molecules (10's to 1000's) and possess colloidal dimensions. *See* R. Laughlin, Advances in liquid crystals, vol. 3, p. 41, 1978. Lipids, and polar lipids in particular, often are considered as surfactants for the purposes of discussion herein, although the term 'lipid' is 20 normally used to indicate that they belong to a subclass of surfactants which have slightly different characteristics than compounds which are normally called surfactants in everyday discussion. Two characteristics which frequently, though not always, are possessed by lipids are, first, they are often of biological origin, and second, they tend to be more soluble in oils and fats than in water. Indeed, many compounds referred to as lipids have extremely low solubilities in water, and thus the presence of a hydrophobic solvent may be necessary in order for the 25 interfacial tension-reducing properties and reversible self-association to be most clearly evidenced, for lipids which are indeed surfactants. Thus, for example, such a compound will strongly reduce the interfacial tension between oil and water at low concentrations, even though extremely low solubility in water might make observation of surface tension reduction in the aqueous system difficult; similarly, the addition of a hydrophobic solvent to a lipid-water system might make the determination of self-association into nanostructured liquid phases and 30 nanostructured liquid crystalline phases a much simpler matter, whereas difficulties associated with high temperatures might make this difficult in the lipid-water system.

Indeed, it has been in the study of nanostructured liquid crystalline structures that the commonality between what had previously been considered intrinsically different -- 'lipids' and 'surfactants' -- came to the forefront, and the two schools of study (lipids, coming from the biological side, and surfactants, coming from the more industrial side) came together as the same nanostructures were observed in lipids as for all surfactants. In addition, it also came to the forefront that certain synthetic surfactants, such as dihexadecyltrimethylammonium bromide, which were entirely of synthetic, non-biological origin, showed 'lipid-like' behavior in that hydrophobic solvents were needed for convenient demonstration of their surfactancy. On the other end, certain lipids such as lysolipids, which are clearly of biological origin, display phase behavior more or less typical of water-soluble surfactants. Eventually, it became clear that for the purposes of discussing and comparing self-association and interfacial tension-reducing properties, a more meaningful distinction was between single-tailed and double-tailed compounds, where single-tailed generally implies water-soluble and double-tailed generally oil-soluble.

Thus, in the present context, any amphiphile which at very low concentrations lowers interfacial tensions between water and hydrophobe, whether the hydrophobe be air or oil, and which exhibits reversible self-association into nanostructured micellar, inverted micellar, or bicontinuous morphologies in water or oil or both, is a surfactant. The class of lipids simply includes a subclass consisting of surfactants which are of biological origin.

**Polar-apolar interface:** In a surfactant molecule, one can find a dividing point (or in some cases, 2 points, if there are polar groups at each end, or even more than two, as in Lipid A, which has seven acyl chains and thus seven dividing points per molecule) in the molecule that divide the polar part of the molecule from the apolar part. In any nanostructured liquid phase or nanostructured liquid crystalline phase, the surfactant forms monolayer or bilayer films; in such a film, the locus of the dividing points of the molecules describes a surface that divides polar domains from apolar domains: this is called the "polar-apolar interface," or "polar-apolar dividing surface." For example, in the case of a spherical micelle, this surface would be approximated by a sphere lying inside the outer surface of the micelle, with the polar groups of the surfactant molecules outside the surface and apolar chains inside it. Care should be taken not to confuse this microscopic interface with macroscopic interfaces, separating two bulk phases, that are seen by the naked eye.

**Bicontinuous:** In a bicontinuous structure, the geometry is described by two distinct, multiply-connected, intertwined subspaces each of which is continuous in all three dimensions; thus, it is possible to traverse the entire span of this space in any direction even if the path is restricted to one or other of the two subspaces. In a bicontinuous structure, each of the subspaces is rich in one type of material or moiety, and the two subspaces are occupied by two such materials or moieties each of which extends throughout the space in all three dimensions.

Sponge, sandstone, apple, and many sinters are examples of relatively permanent though chaotic bicontinuous structures in the material realm. In these particular examples, one of the subspaces is occupied by a solid that is more or less deformable and the other subspace, though it may be referred to as void, is occupied by a fluid. Certain lyotropic liquid crystalline states are also examples, one subspace being occupied by amphiphile molecules oriented and aggregated into sheet-like arrays that are ordered geometrically, the other subspace being occupied by solvent molecules. Related liquid crystalline states that contain two incompatible kinds of solvent molecules, e.g., hydrocarbon and water, present a further possibility in which one subspace is rich in the first solvent, the other in the second, and the surface between lies within a multiply connected stratum rich in oriented surfactant molecules. Certain equilibrium microemulsion phases that contain comparable amounts of hydrocarbon and water as well as amphiphilic surfactant may be chaotic bicontinuous structures, maintained in a permanent state of fluctuating disorder by thermal motions, for they give no evidence of geometric order but there is compelling evidence for multiple continuity. Bicontinuous morphologies occur also in certain phase-segregated block copolymers. *See* Anderson, D.M., Davis, H.T., Nitsche, J.C.C. and ~~—~~ Scriven, L.E. (1990) *Advances in Chemical Physics*, 77:337.

**Chemical criteria:** In the case of surfactants, a number of criteria have been tabulated and discussed in detail by Robert Laughlin for determining whether a given polar group is functional as a surfactant head group, where the definition of surfactant includes the formation, in water, of nanostructured phases even at rather low concentrations. R. Laughlin, *Advances in Liquid Crystals*, 3:41, 1978.

The following listing given by Laughlin gives some polar groups which are not operative as surfactant head groups — and thus, for example, an alkane chain linked to one of these polar groups would not be expected to form nanostructured liquid or liquid crystalline phases — are: aldehyde, ketone, carboxylic ester, carboxylic acid, isocyanate, amide, acyl cyanoguanidine, acyl

guanylurea, acyl biuret, N,N-dimethylamide, nitrosoalkane, nitroalkane, nitrate ester, nitrite ester, nitrone, nitrosamine, pyridine N-oxide, nitrile, isonitrile, amine borane, amine haloborane, sulfone, phosphine sulfide, arsine sulfide, sulfonamide, sulfonamide methylimine, alcohol (monofunctional), ester (monofunctional), secondary amine, tertiary amine, mercaptan, thioether, 5 primary phosphine, secondary phosphine, and tertiary phosphine.

Some polar groups which are operative as surfactant head groups, and thus, for example, an alkane chain linked to one of these polar groups would be expected to form nanostructured liquid and liquid crystalline phases, are:

- a. Anionics: carboxylate (soap), sulfate, sulfamate, sulfonate, thiosulfate, sulfinate, phosphate, phosphonate, phosphinate, nitroamide, tris(alkylsulfonyl)methide, xanthate;
- 10 b. Cationics: ammonium, pyridinium, phosphonium, sulfonium, sulfoxonium;
- c. Zwitterionics: ammonio acetate, phosphoniopropane sulfonate, pyridinioethyl sulfate;
- d. Semipolars: amine oxide, phosphoryl, phosphine oxide, arsine oxide, sulfoxide, sulfoximine, sulfone diimine, ammonio amide.

15 Laughlin also demonstrates that as a general rule, if the enthalpy of formation of a 1:1 association complex of a given polar group with phenol (a hydrogen bonding donor) is less than 5 kcal, then the polar group will not be operative as a surfactant head group.

In addition to the polar head group, a surfactant requires an apolar group, and again there are guidelines for an effective apolar group. For alkane chains, which are of course the most 20 common, if  $n$  is the number of carbons, then  $n$  must be at least 6 for surfactant association behavior to occur, although at least 8 or 10 is the usual case. Interestingly octylamine, with  $n = 8$  and the amine head group which is just polar enough to be effective as a head group, exhibits a lamellar phase with water at ambient temperature, as well as a nanostructured L2 phase.

25 Warnheim, T., Bergenstahl, B., Henriksson, U., Malmvik, A.-C. and Nilsson, P. (1987) J. of Colloid and Interface Sci. 118:233. Branched hydrocarbons yield basically the same requirement on the low  $n$  end; for example, sodium 2-ethylhexylsulfate exhibits a full range of liquid crystalline phases. Winsor, P.A. (1968) Chem. Rev. 68:1. However, the two cases of linear and branched hydrocarbons are vastly different on the high  $n$  side. With linear, saturated alkane chains, the tendency to crystallize is such that for  $n$  greater than about 18, the Krafft temperature 30 becomes high and the temperature range of nanostructured liquid and liquid crystalline phases increases to high temperatures, near or exceeding 100° C; in the context of the present invention, for most applications this renders these surfactants considerably less useful than those with  $n$

between 8 and 18. With the introduction of unsaturation or branching in the chains, the range of n can increase dramatically. The case of unsaturation can be illustrated with the case of lipids derived from fish oils, where chains with 22 carbons can have extremely low melting points, due to the presence of as many as 6 double bonds, as in docosahexaenoic acid and its derivatives, 5 which include monoglycerides, soaps, etc. Furthermore, polybutadiene of very high MW is an elastomeric polymer at ambient temperature, and block copolymers with polybutadiene blocks are well known to yield nanostructured liquid crystals. Similarly, with the introduction of branching, one can produce hydrocarbon polymers such as polypropyleneoxide (PPO), which serves as the hydrophobic block in a number of amphiphilic block copolymer surfactants of great 10 importance, such as the PLURONIC series of surfactants. Substitution of fluorine for hydrogen, in particular the use of perfluorinated chains, in surfactants generally lowers the requirement on the minimal value of n, as exemplified by lithium perfluouroctanoate (n=8), which displays a full range of liquid crystalline phases, including an intermediate phase which is fairly rare in surfactant systems. As discussed elsewhere, other hydrophobic groups, such as the fused-ring 15 structure in the cholate soaps (bile salts), also serve as effective apolar groups, although such cases must generally be treated on a case by case basis, in terms of determining whether a particular hydrophobic group will yield surfactant behavior.

For single-component block copolymers, relatively simple mean-field statistical theories are sufficient to predict when nanostructure liquid phase and liquid crystalline phase materials 20 will occur, and these are quite general over a wide range of block copolymers. If  $\chi$  is the Flory-Huggins interaction parameter between polymer blocks A and B, and N is the total index of polymerization (defined as the number of statistical units, or monomer units, in the polymer chain, consistently with the definition of the interaction parameter) of the block copolymer, then nanostructured liquid and liquid crystalline phases are expected when the product  $\chi N$  is greater 25 than 10.5. Leibler, L. (1980) Macromolecules 13:1602. For values comparable to, but larger than, this critical value of 10.5, ordered nanostructured (liquid crystalline) phases can occur, including even bicontinuous cubic phases. Hajduk, D.A., Harper, P.E., Gruner, S.M., Honeker, C.C., Kim, G., Thomas, E.L. and Fetter, L.J. (1994) Macromolecules 27:4063.

The nanostructured liquid phase material suitable for the nanostructured material of the 30 matrix may be:

- a. a nanostructured L1 phase material,
- b. a nanostructured L2 phase material,

- c. a nanostructured microemulsion or
- d. a nanostructured L3 phase material.

5 The nanostructured liquid phases are characterized by domain structures, composed of domains of at least a first type and a second type (and in some cases three or even more types) having the following properties:

- a) the chemical moieties in the first type domains are incompatible with those in the second type domains (and in general, each pair of different domain types are mutually incompatible) such that they do not mix under the given conditions but rather remain as separate domains; (for example, the first type domains could be composed substantially of polar moieties such as water and lipid head groups, while the second type domains could be composed substantially of apolar moieties such as hydrocarbon chains: or, first type domains could be polystyrene-rich, while second type domains are polyisoprene-rich, and third type domains are polyvinylpyrrolidone-rich);
- b) the atomic ordering within each domain is liquid-like rather than solid-like, i.e., it lacks lattice-ordering of the atoms; (this would be evidenced by an absence of sharp Bragg peak reflections in wide-angle x-ray diffraction);
- c) the smallest dimension (e.g., thickness in the case of layers, diameter in the case of cylinder-like or sphere-like domains) of substantially all domains is in the range of nanometers (viz., from about 1 to about 100 nm); and
- 20 d) the organization of the domains does not exhibit long-range order nor conform to any periodic lattice. This is evidenced by the absence of sharp Bragg reflections in small-angle x-ray scattering examination of the phase. (Furthermore, as seen below, if high viscosity and birefringence are both lacking, this is strong evidence of a liquid, as opposed to liquid crystalline, phase.)

25 With respect to each of the liquid phases, systems based on surfactants, where the two types of domains in the nanostructured liquid are 'polar' and 'apolar,' are initially discussed. Generally, following that, systems based on block copolymers are discussed. In these systems the terms 'polar' and 'apolar' may or may not be applicable, but there exist domain types 'A', 'B', etc., where as defined above (in the definition of a nanostructure liquid) domain types 'A' and 'B' 30 are immiscible with respect to each other.

**L1 phase:** In an L1 phase that occurs in a system based on surfactants, the curvature of

the polar-apolar interface is toward the apolar (non-polar) regions, generally resulting in particles -- normal micelles -- that exist in a water-continuous medium. (Here "water" refers to any polar solvent). When these micelles transform from spherical to cylindrical as conditions or compositions change, they can start to fuse together and bicontinuity can result. In addition to the water continuity, the hydrophobic domains can connect up to form a sample-spanning network; this can still be an L1 phase. In addition, there are examples of L1 phases that show evidence of having no microstructure whatsoever. That is, there are no micelles, no well-defined domains, just surfactant molecules co-mingled in a structureless, one-phase liquid solution that is thus not a nanostructured material. These "structureless solutions" can sometimes be changed to nanostructured phases by simple change in composition without any phase change in between. In other words, thermodynamics does not dictate a phase boundary between a structureless solution and a nanostructured phase. This is, of course, in contrast with the case of a transition between a phase having long-range order (a liquid crystal or a crystal) and a phase lacking long-range order (a liquid), where a phase boundary is required by thermodynamics.

For L1 phases that occur in systems based on block copolymers, the terms 'polar' and 'apolar' may not apply, but in any case there are two (or in some cases more) domain types; we make the convention that the curvature of the A/B interface is toward A domains, so that a typical nanostructure would consist of particles, often sphere-like, of domain type A located in a continuum of B domains. As an example, in polystyrene-polyisoprene diblock copolymers, if the volume fraction of polystyrene blocks is very low, say 10%, then the usual microstructure will be polystyrene-rich spheres in a continuous polyisoprene matrix. Contrariwise, polyisoprene-rich spheres in a polystyrene-continuous matrix would be the likely structure for a 10% polyisoprene PS-PI diblock.

Identification of the nanostructured L1 phase. Since the L1 phase is a liquid phase, techniques have been developed to distinguish the nanostructured L1 phase from unstructured solution liquid phases. In addition to the experimental probes that are discussed below, there is a well-known body of knowledge that provides criteria by which one can determine *a priori* whether a given system should be expected to form nanostructured phases instead of simple unstructured solutions.

Since the formation of nanostructured liquid phases and nanostructured liquid crystalline phases is one requirement in the definition of a surfactant, in the discrimination of a nanostructured liquid from an unstructured solution it is extremely valuable to have criteria for

determining whether a given compound is in fact a surfactant. criteria which provide for a number of tests for surfactancy in addition to methods discussed below for directly analyzing the liquid in question. A number of criteria have been discussed by Robert Laughlin in *Advances in liquid crystals*, 3:41, 1978. To begin with, Laughlin lists chemical criteria for determining *a priori*

whether a given compound will be a surfactant, and this was discussed in detail above. If, based on these criteria, a compound is expected to be a true surfactant, then the compound is expected to form nanostructured phases in water. In addition, with such a compound in the presence of water and hydrophobe, nanostructured phases are also expected to form, normally incorporating at least a portion of the hydrophobe present.

In the event that a non-surfactant amphiphile is added to such a system, and in particular an amphiphilic organic solvent such as a short-chained alcohol, dioxane, tetrahydrofuran, dimethylformamide, acetonitrile, dimethylsulfoxide, etc., then structureless liquids could form, as the action of the organic solvent will generally be to disrupt colloidal aggregates and co-solubilize all the components.

Laughlin also goes on to discuss a number of criteria based on physical observations. One well-known criteria is the critical micelle concentration (CMC) which is observed in surface tension measurements. If the surface tension of an aqueous solution of the compound in question is plotted as a function of the concentration, then at very low concentrations, the surface tension will be seen to drop off sharply if the added compound is indeed a surfactant. Then, at a particular concentration known as the CMC, a sharp break will occur in this plot, as the slope of the line decreases drastically to the right of the CMC, so that the surface tension decreases much less with added surfactant. The reason is that above the CMC, added surfactant goes almost entirely into the creation of micelles, rather than to the air-water interface.

A second criterion tabulated by Laughlin is the liquid crystal criterion: if the compound forms liquid crystals at high concentrations, then it must be a surfactant and will form liquid crystalline phases at concentrations lower than those at which the occur. In particular, the L1 phase is usually found at concentrations of surfactant just lower than those that form normal hexagonal, or in some cases normal non-bicontinuous cubic, phase liquid crystals.

Another criterion discussed by Laughlin is based on the temperature differential between the upper limit of the Krafft boundary plateau and the melting point of the anhydrous compound. The Krafft boundary is a curve in the phase diagram of the binary system with compound and water; below the Krafft line are crystals, and above the Krafft line the crystals melt, so that there

is a dramatic increase in solubility over a very narrow temperature range along the Krafft line. In the case of a true surfactant, this temperature differential is substantial: for example, in sodium palmitate, the melting point of the anhydrous compound is 288°C, while the Krafft line has its plateau at 69°C, so that the differential is 219°C. Laughlin goes on to discuss the case of 5 dodecylamine, which has a temperature differential of 14°C, and has a small region in the phase diagram corresponding to liquid crystals, thus indicating a modest degree of association colloid behavior. In contrast, neither dodecylmethylamine nor dodecanol exhibit association behavior of the surfactant type, and both have zero temperature differential.

As in the case of liquid crystals, as discussed herein, given a material there are a number 10 of experimental probes one can use to determine whether or not the material, in this case a liquid, is nanostructured, and these will be discussed in the context of the L1 phase, although they apply to all nanostructured liquids-- with the appropriate modifications. In such a determination, it is best to combine as many of these characterizations as feasible.

As with all the liquid phases, the L1 phase is optically isotropic in the absence of flow. It 15 does not give a splitting in the <sup>2</sup>H NMR bandshape with deuterated surfactant.

Also, in examination with crossed polarizing filters, the L1 phase of surfactant systems does not generally give birefringence even under moderate flow conditions. The situation with respect to birefringence in the case of block copolymer-based systems is complicated by the possibility of strain birefringence, so this is not a reliable method in that case.

20 Returning to the surfactant-based L1 phase, viscosity is generally quite low, considerably lower than any liquid crystals in the same system.

Using pulsed-gradient NMR to measure the effective self-diffusion coefficients of the 25 various components, one finds that the self-diffusion of surfactant, and any added hydrophobe, is very low, typically on the order of 10<sup>-13</sup> m<sup>2</sup>/sec or less (unless the phase is bicontinuous; see below.) This is because the primary means for diffusion of surfactant and hydrophobe is by diffusion of entire micelles, which is very slow. Also, the diffusion rates of surfactant and of hydrophobe should be nearly the same, for the same reason.

Small-angle x-ray scattering (SAXS) does not give sharp Bragg peaks in the nanometer range (nor any range), of course. However, analysis of the entire curve by several methods from 30 the literature can give the length scale of the nanostructure. By analyzing the falloff of intensity at low wave numbers (but not too low compared to the inverse of the surfactant molecule length), one can determine the apparent radius of gyration: one plots intensity versus the square of the

wave number, and takes the slope, to deduce  $R_g$  (the so-called Guinier plot.) The radius of gyration is then related to the dimensions of the micellar units by standard well-known formulae. This will fall in the range of nanometers. In addition, by plotting the product of intensity times the square of the wave number, versus the wave number -- the so-called 'Hosemann plot' -- one 5 will find a peak that can also be related to the dimensions of the micelles; this has the advantage that it is less sensitive to interactions between micelles than is the radius of gyration.

For surfactant-based L1 phases which are bicontinuous, the above will change as follows. First, the viscosity can increase considerably when bicontinuity occurs, due to the rigidity of the surfactant film, which is continuous. Also, the self-diffusion rate of the surfactant and even of 10 added hydrophobe (which can be deliberately added to a binary system as a marker) can increase dramatically, approaching or even exceeding the values in a lamellar phase in the same system. And while SAXS analyses, both the radius of gyration and the Hosemann plot, will give resulting dimensions in the nanometer range, these must be interpreted as characteristic length 15 scales of the bicontinuous domain structure, rather than as dimensions of discrete particles. (In some models, such as the interconnected cylinders model of the author's thesis, or the Talmon-Prager model, a bicontinuous domain structure is represented as made up of units, which although seemingly 'particles', are in reality only building blocks for construction of a model bicontinuous geometry).

For L1 phases in block copolymer-based systems, this same SAXS analysis holds. In 20 contrast, NMR bandshape and self-diffusion measurements in general do not carry over, nor do surface tension measurements. However, vapor transport measurements have been used in the past in place of NMR self-diffusion. In particular, if one can find a gas which is preferentially soluble in one of the domain types, but not in the other(s), then one can test for continuity of 25 those domains by measuring the transport of that gas through the sample. If this is possible, then transport through the continuous domains (type B) in the micellar phase should be only slightly slower than that in the pure B polymer, whereas gas transport for a gas confined to A domains should be very low.

The shear modulus of a block copolymer-based micellar phase is determined largely by 30 that of the polymer block forming the continuous domains, polymer B in our convention. Thus, for example, in a PS-PI diblock which is 10% PS, so that PS micelles form in a continuous PI matrix, the shear modulus would be close to that of pure polyisoprene, with only a slight increase due to the presence of the PS micelles. Interestingly, in the reverse case, with 90% PS and thus

PI micelles in a continuous PS matrix, the elastomeric PI micelles can provide a shock-absorbing component which can improve the fracture characteristics over those of pure, glassy polystyrene.

5 **L2 phase:** This phase is the same as the L1 phase except that the roles of the polar region and the apolar region are reversed: the curvature of the polar-apolar interface is toward the polar domains, the interior of the micelles (if they exist) is water and/or other polar moieties, and the apolar domains (typically alkane chains of a lipid) form a continuous matrix -- although it is possible for the polar domains also to connect up to form a bicontinuous L2 phase. As above, this phase can be either nanostructured or structureless.

10 Identification of the nanostructured L2 phase. The guidelines for making an identification of the nanostructured L2 phase are the same as those given above for the L1 phase, with the following modifications. We need only discuss the surfactant-based L2 phase, since in the block copolymer-based systems the two types of micellar phases (A in B, and B in A) are equivalent, and above we discussed the identification of the micellar phase in block copolymer 15 systems.

20 First, L2 phases are generally more prominent when the HLB is low, for example with ethoxylated alcohol surfactants having a small number of ethylene oxide groups (usually 5 or less, with typical alkyl chain lengths), or with double-chained surfactants. In terms of phase behavior, they generally occur at higher surfactant concentrations than even the reversed liquid crystalline phases; a location that is very common is for the L2 phase to border the reversed hexagonal phase at higher surfactant concentrations. For L2 phases which are not bicontinuous, it 25 is the water self-diffusion which is very low, and measurement of the diffusion coefficient (by pulsed-gradient NMR, for example) should give a number on the order of  $10^{-11} \text{ m}^2/\text{sec}$  or less. Also, a Hosemann plot will give the size of the reversed micelles, which will essentially be the water domain size.

**Microemulsion:** A microemulsion may be defined as a thermodynamically stable, low viscosity, optically isotropic, microstructured liquid phase containing oil (apolar liquid), water (polar liquid), and surfactant. *See also* Danielsson, I. and Lindman, B. (1981) *Colloids and Surfaces*, 3:391. Thermodynamically stable liquid mixtures of surfactant, water and oil are

usually referred to as microemulsions. While being macroscopically homogeneous, they are structured on a microscopic length scale (10-1,000 Angstrom) into aqueous and oleic microdomains separated by a surfactant-rich film. See Skurtveit, R. and Olsson, U. (1991) J. Phys. Chem. 95:5353. A key defining feature of a microemulsion is that it contain an "oil" (apolar solvent or liquid), in addition to water and surfactant; it is always microstructured by definition. In general, because of the strong tendency for oil and water to phase segregate, in the absence of an organic solvent capable of co-solubilizing oil and water (such as ethanol, THF, dioxane, DMF, acetonitrile, dimethylsulfoxide, and a few others), a clear, single-phase liquid containing oil, water and surfactant must be a microemulsion, and one can safely conclude on that basis alone that the phase is nanostructured. Note that a microemulsion can also be an L1 or L2 phase, especially if it contains well-defined micelles; however, if it is an L1 phase, then the micelles are necessarily swollen with oil. The microemulsion is a nanostructured liquid phase. If a liquid with "oil," water and surfactant has a characteristic domain size larger than the nanometer range, that is, in the micron range, then it is no longer a microemulsion but rather a "miniemulsion" or plain emulsion; both of the latter are non-equilibrium. The term microemulsion was introduced, despite the fact that L1 and L2 phases can contain oil, and can even be bicontinuous, because it is fairly common for three-component oil-water-surfactant/lipid systems to evolve continuously from water-continuous to bicontinuous to oil-continuous with no phase boundaries in between. In this case, it does not make sense to try to set a dividing point between the "L1" and "L2" regions of the phase diagram; so instead, one just refers to the whole region as "microemulsion" -- recognizing that at the high-water-content end of this region the structure is that of an oil-swollen L1 phase, and at the high-oil-content end of this region the structure is that of an L2 phase. (In terms of Venn diagrams, there are overlaps between microemulsions and L1 and L2 phases, though not between L1 and L2 phases.) As discussed below, the microstructure of microemulsions is quite generally describable in terms of a monolayer film of surfactant that divides oil-rich domains from water-rich domains. This surfactant/lipid-rich dividing film can enclose to form micelles, or connect up into a network structure to form a bicontinuous microemulsion.

It must be pointed out that an emulsion is not a nanostructured liquid, as the term is applied herein. To begin with, the characteristic length scale in an emulsion, which essentially is the average size of an emulsion droplet, is generally much larger than the characteristic length scale in a nanostructured liquid, and falls in the range of microns instead of nanometers. While

recent efforts to produce emulsions with submicron droplet sizes have given rise to smaller-droplet emulsions and to the advent of the term "mini emulsion," there remain crucial differences which exclude emulsions and mini emulsions from the realm of nanostructured liquid phases as applied herein. The nanostructured liquid phases described herein, including microemulsions, 5 exist at thermodynamic equilibrium, in contrast to emulsions which are not equilibrium phases but only metastable materials. Furthermore, a nanostructured liquid which is acquiescent and fully equilibrated is optically transparent, whereas an emulsion is generally opaque -- ordinary milk is an emulsion, for example. In addition, if one takes the model of Friberg for the structure 10 of an ordinary emulsion to be true, and this is generally recognized in the field, then the distinction at the molecular scale can be seen to be dramatic. According to that model, emulsion droplets can generally be seen to be stabilized by interfacial films, which upon microscopic examination typically prove to be films of nanostructured liquid crystalline phase material: thus, these emulsions have a hierarchical structure in which a nanostructured phase plays the role of a stabilizing layer between the main building blocks, which are the emulsion droplets and the 15 continuous medium. Our use of the term "nanostructured" instead of "microstructured" is based on the more precise and restricted nature of the term "nanostructured" and its exclusion of other liquid phases which fall into an entirely different realm, such as emulsions. Clearly, simple geometric considerations dictate that an emulsion which has droplets on the order of 10 microns in size, and a stabilizing film which may be a liquid crystalline layer, is not appropriate as the 20 interior of a microparticle of the present invention which generally has a size on the order of 1 micron.

Determination of nanostructured microemulsions. The methods and guidelines discussed above for determination of nanostructured L1 phases carry over to the determination of nanostructured microemulsion phases, with the following variations.

25 For microemulsions which do not clearly fall under either the L1 phase or the L2 phase descriptions -- which is the remaining case to be treated here -- we take note that many, if not most, of these are bicontinuous, and in the context of a single liquid phase containing oil, water and surfactant, bicontinuity provides strong proof that the phase is nanostructured, since emulsions and other common liquids are never bicontinuous. This issue has been addressed in 30 "On the demonstration of bicontinuous structures in microemulsions," Lindman, B., Shinoda, K., Olsson, U., Anderson, D. M., Karlstrom, G. and Wennerstrom, H. (1989) *Colloids and Surfaces* 38:205. The time-tested way to demonstrate bicontinuity is to use pulsed-gradient NMR, and

measure the effective self-diffusion coefficients of both oil and water separately; generally it is best to measure also the self-diffusion of the surfactant. Electrical conductivity can also be used to establish water continuity, although this is prone to problems associated with "hopping" processes. Fluorescence quenching has also been used for continuity determination. Sanchez-

5 Rubio, M., Santos-Vidals, L. M., Rushforth, D. S. and Puig, J. E. (1985) *J. Phys. Chem.* 89:411. Small-angle neutron and x-ray scattering analyses have been used to examine bicontinuity.

Auvray, L., Cotton, R., Ober, R. and Taupin, J. (1984) *J. Phys. Chem.* 88:4586. Porod analysis of SAXS curves has been used to deduce the presence of interfaces, thus proving that a nanostructure is present. Martino, A. and Kaler, E.W. (1990) *J. Phys. Chem.* 94:1627. Freeze-10 fracture electron microscopy, with extremely fast rates of freezing, has been used to study microemulsions. and is the result of decades of development on fixation methods for nanostructured liquids: a critical review discussing the methods and the reliability of the results has been given. Talmon, Y.. in K.L. Mittal and P. Bothorel (Eds), Vol. 6. Plenum Press. New York, 1986, p. 1581.

15 In the event that an oil-water-surfactant liquid phase is not clearly an L1 or L2 phase, and does not show strong evidence of bicontinuity, then the analysis to demonstrate that it is nanostructured can be fairly involved, and no single technique will suffice. In general, one would apply the measurements discussed in this section, such as SANS or SAXS, NMR self-diffusion, cryo EM, etc., to attempt to rationalize the data within the context of a model 20 nanostructure.

25 **L3 phase:** L2-phase regions in phase diagrams sometimes exhibit "tongues" sticking out of them: long, thin protrusions unlike the normal appearance of a simple L2 phase region. This sometimes appears also with some L1 regions, as described below. When one examines these closely, especially with X-ray and neutron scattering, they differ in a fundamental way from L2 phases. In an L2 phase, the surfactant film is generally in the form of a monolayer, with oil (apolar solvent ) on one side and water (polar solvent) on the other. By contrast, in this "L3 phase," as these phases are called, the surfactant is in the form of a bilayer, with water (polar solvent) on both sides. The L3 phase is generally considered to be bicontinuous and, in fact, it shares another property with cubic phases: there are two distinct aqueous networks, interwoven 30 but separated by the bilayer. So, the L3 phase is really very similar to the cubic phase, but lacking the long-range order of the cubic phase. L3 phases stemming from L2 phases and those

stemming from L1 phases are given different names. "L3 phase" is used for those associated to L2 phases, and "L3\* phase" for those associated to L1 phases.

Determination of the nanostructured L3 phase. Determination of the L3 phase in distinction to the other liquid phases discussed herein can be a sophisticated problem, requiring the combination of several analyses. The most important of these techniques are now discussed.

In spite of its optical isotropy when acquiescent and the fact that it is a liquid, the L3 phase can have the interesting property that it can exhibit flow birefringence. Often this is associated with fairly high viscosity, viscosity that can be considerably higher than that observed in the L1 and L2 phases, and comparable to or higher than that in the lamellar phase. These properties are of course a result of the continuous bilayer film, which places large constraints on the topology, and the geometry, of the nanostructure. Thus, shear can result in the cooperative deformation (and resulting alignment) of large portions of the bilayer film, in contrast with, for example, a micellar L1 phase, where independent micellar units can simply displace with shear, displace with shear, and in any case a monolayer is generally much more deformable under shear than a bilayer. Support for this interpretation comes from the fact that the viscosity of L3 phases is typically a linear function of the volume fraction of surfactant. Snabre, P. and Porte, G. (1990) *Europhys. Lett.* 13:641.

Sophisticated light, neutron, and x-ray scattering methodologies have been developed for determination of nanostructured L3 phases. Safinya, C.R., Roux, D., Smith, G.S., Sinha, S.K., Dimon, P., Clark, N.A. and Bellocq, A.M. (1986) *Phys. Rev. Lett.* 57:2718; Roux, D. and Safinya, C.R. (1988) *J. Phys. France* 49:307; Nallet, F., Roux, D. and Prost, J. (1989) *J. Phys. France* 50:3147. The analysis of Roux, et al., in Roux, D., Cates, M.E., Olsson, U., Ball, R.C., Nallet, F. and Bellocq, A.M., *Europhys. Lett.* purportedly is able to determine that the nanostructure has two aqueous networks, separated by the surfactant bilayer, which gives rise to a certain symmetry due to the equivalence of the two networks.

Fortunately, determination of the nanostructured nature of an L3 phase based on phase behavior can be more secure than in the case of typical L1, L2 or even microemulsion phases. This is first of all because the L3 phase is often obtained by addition of a small amount (a few percent) of oil or other compound to a lamellar or bicontinuous cubic phase, or small increase of temperature to these same phases. Since these liquid crystalline phases are easy to demonstrate to be nanostructured (Bragg peaks in X-ray, in particular), one can be confident that the liquid phase is also nanostructured when it is so close in composition to a liquid crystalline phase.

After all, it would be extremely unlikely that the addition of a few percent of oil to a nanostructured liquid crystalline phase would convert the liquid crystal to a structureless liquid. Indeed, pulsed-gradient NMR self-diffusion measurements in the Aerosol OT - brine system show that the self-diffusion behavior in the L3 phase extrapolates very clearly to those in the 5 nearby reversed bicontinuous cubic phase. This same L3 phase has been the subject of a combined SANS, self-diffusion, and freeze-fracture electron microscopy study. Strey, R., Jahn, W., Skouri, M., Porte, G., Marignan, J. and Olsson, U., in "Structure and Dynamics of Supramolecular Aggregates," S.H. Chen, J.S. Huang and P. Tartaglia, Eds., Kluwer Academic Publishers, The Netherlands. Indeed, in SANS and SAXS scattering analysis of L3 phases, a 10 broad interference peak is often observed at wave vectors that correspond to d-spacings that are the same order of magnitude as those in bicontinuous cubic phases that are nearby in the phase diagram, and the author has developed a model for L3 phase nanostructure which is an extrapolation of known structures for bicontinuous cubic phases. Anderson, D.M., Wennerström, H. and Olsson, U. (1989) J. Phys. Chem. 93:4532.

15 As a component of the coated particle the nanostructured liquid crystalline phase material may be

- a. a nanostructured normal or reversed cubic phase material,
- b. a nanostructured normal or reversed hexagonal phase material,
- c. a nanostructured normal or reversed intermediate phase material or
- d. a nanostructured lamellar phase material.

20 The nanostructured liquid crystalline phases are characterized by domain structures, composed of domains of at least a first type and a second type (and in some cases three or even more types of domains) having the following properties:

25 a) the chemical moieties in the first type domains are incompatible with those in the second type domains (and in general, each pair of different domain types are mutually incompatible) such that they do not mix under the given conditions but rather remain as separate domains; (for example, the first type domains could be composed substantially of polar moieties such as water and lipid head groups, while the second type domains could be composed substantially of apolar moieties such as hydrocarbon chains; or, first type domains could be 30 polystyrene-rich, while second type domains are polyisoprene-rich, and third type domains are polyvinylpyrrolidone-rich);

b) the atomic ordering within each domain is liquid-like rather than solid-like, lacking

lattice-ordering of the atoms; (this would be evidenced by an absence of sharp Bragg peak reflections in wide-angle x-ray diffraction);

5           c) the smallest dimension (e.g., thickness in the case of layers, diameter in the case of cylinders or spheres) of substantially all domains is in the range of nanometers (viz., from about 1 to about 100 nm); and

10           d) the organization of the domains conforms to a lattice, which may be one-, two-, or three-dimensional, and which has a lattice parameter (or unit cell size) in the nanometer range (viz., from about 5 to about 200 nm); the organization of domains thus conforms to one of the 230 space groups tabulated in the International Tables of Crystallography, and would be evidenced in a well-designed small-angle x-ray scattering (SAXS) measurement by the presence of sharp Bragg reflections with d-spacings of the lowest order reflections being in the range of 3-200 nm.

**Lamellar phase:** The lamellar phase is characterized by:

15           1. Small-angle x-ray shows peaks indexing as 1:2:3:4:5 . . . in wave number.

20           2. To the unaided eye, the phase is either transparent or exhibits mild or moderate turbidity.

25           3. In the polarizing optical microscope, the phase is birefringent, and the well-known textures have been well described by Rosevear, and by Winsor (e.g., Chem. Rev. 1968, p.1). The three most pronounced textures are the "Maltese crosses," the "mosaic" pattern, and the "oily streaks" patterns. The Maltese cross is a superposition of two dark bands (interference fringes) roughly perpendicular to each other, over a roughly circular patch of light (birefringence), forming a distinctive pattern reminiscent of the WWI German military symbol. The variations on this texture, as well as its source, is thoroughly described in J. Bellare, Ph.D. Thesis, Univ. of Minnesota, 1987. The "mosaic" texture can be envisioned as the result of tightly packing together a dense array of deformed Maltese crosses, yielding dark and bright patches randomly quilted together. The "oily streaks" pattern is typically seen when the (low viscosity) lamellar phase flows between glass and coverslip; in this pattern, long curved lines are seen, upon close inspection under magnification (e.g., 400x), to be composed of tiny striations which run roughly perpendicular to the line of the curve, as ties make up a railroad track (to be contrasted with the hexagonal texture discussion below). In some cases, particularly if the phase is massaged gently between glass and coverslip for a period of time, the lamellar phase will align

with its optic axis parallel to the line of sight in the microscope, resulting in a disappearance of the birefringence.

For lamellar phases in surfactant-water systems:

1. viscosity is low, enough so that the material flows (e.g., when a tube containing  
5 the phase is tipped upside down).

2. the self-diffusion rates of all components are high, comparable to their values in bulk -- e.g., the effective self-diffusion coefficient of water in the lamellar phase is comparable to that in pure water. Since the surfactants that form liquid crystals are usually not liquid at ambient temperatures, the reference point for the self-diffusion coefficient of the surfactant is not  
10 clear-cut, and in fact, the effective (measured) self-diffusion coefficient of the surfactant in the lamellar phase is often taken to be the reference point for interpreting measurements in other phases.

15 3. if the surfactant is deuterated in the head group, and the  $^2\text{H}$  NMR bandshape measured, one finds two spikes with the splitting between them twice what it is in the hexagonal phase.

20 4. in terms of phase behavior, the lamellar phase generally occurs at high surfactant concentrations in single-tailed surfactant / water systems, typically above 70% surfactant; in double-tailed surfactants, it often occurs at lower concentrations, often extending well below 50%. It generally extends to considerably higher temperatures than do any other liquid crystalline phases that happen to occur in the phase diagram.

For lamellar phases in single-component block copolymer systems:

1. shear modulus is generally lower than other liquid crystalline phases in the same system.

25 2. in terms of phase behavior, the lamellar phase generally occurs at volume fractions of the two blocks is roughly 50:50.

**Normal hexagonal phase:** The normal hexagonal phase is characterized by:

1. Small-angle x-ray shows peaks indexing as  $1:\sqrt{3}:2:\sqrt{7}:3\dots$ ; in general,  $\sqrt{(h^2 + hk + k^2)}$ , where  $h$  and  $k$  are integers -- the Miller indices of the two-dimensional symmetry group.

30 2. To the unaided eye, the phase is generally transparent when fully equilibrated, and thus often considerably clearer than any nearby lamellar phase.

3. In the polarizing optical microscope, the phase is birefringent, and the well-known textures have been well described by Rosevear, and by Winsor (e.g., Chem. Rev. 1968, p.1). The most distinctive of these is the "fan-like" texture. This texture appears to be made up of patches of birefringence, where within a given patch, fine striations fan out giving an appearance reminiscent of an oriental fan. Fan directions in adjacent patches are randomly oriented with respect to each other. A key difference distinguishing between lamellar and hexagonal patterns is that the striations in the hexagonal phase do not, upon close examination at high magnification, prove to be composed of finer striations running perpendicular to the direction of the larger striation, as they do in the lamellar phase.

10 For normal hexagonal phases in surfactant-water systems:

1. viscosity is moderate, more viscous than the lamellar phase but far less viscous than typical cubic phases (which have viscosities in the millions of centipoise).

2. the self-diffusion coefficient of the surfactant is slow compared to that in the lamellar phase: that of water is comparable to that in bulk water.

15 3. the  $^2\text{H}$  NMR bandshape using deuterated surfactant shows a splitting, which is one-half the splitting observed for the lamellar phase.

20 4. in terms of phase behavior, the normal hexagonal phase generally occurs at moderate surfactant concentrations in single-tailed surfactant / water systems, typically on the order of 50% surfactant. Usually the normal hexagonal phase region is adjacent to the micellar (L1) phase region, although non-bicontinuous cubic phases can sometimes occur in between. In double-tailed surfactants, it generally does not occur at all in the binary surfactant-water system.

25 For hexagonal phases in single-component block copolymer systems, the terms "normal" and "reversed" do not generally apply (although in the case where one block is polar and the other apolar, these qualifiers could be applied in principle). The shear modulus in such a hexagonal phase is generally higher than a lamellar phase, and lower than a bicontinuous cubic phase, in the same system. In terms of phase behavior, the hexagonal phases generally occurs at volume fractions of the two blocks on the order of 35:65. Typically, two hexagonal phases will straddle the lamellar phase, with, in each case, the minority component being inside the cylinders (this description replacing the 'normal/reversed' nomenclature of surfactant systems).

30 **Reversed hexagonal phase:** In surfactant-water systems, the identification of the reversed hexagonal phase differs from the above identification of the normal hexagonal phase in

only two respects:

1. The viscosity of the reversed hexagonal phase is generally quite high, higher than a typical normal hexagonal phase, and approaching that of a reversed cubic phase. And,
2. In terms of phase behavior, the reversed hexagonal phase generally occurs at high surfactant concentrations in double-tailed surfactant / water systems, often extending to, or close to, 100% surfactant. Usually the reversed hexagonal phase region is adjacent to the lamellar phase region which occurs at lower surfactant concentration, although bicontinuous reversed cubic phases often occur in between. The reversed hexagonal phase does appear, somewhat surprisingly, in a number of binary systems with single-tailed surfactants, such as those of many monoglycerides (include glycerol monooleate), and a number of nonionic PEG-based surfactants with low HLB.

As stated above in the discussion of normal hexagonal phases, the distinction between 'normal' and 'reversed' hexagonal phases makes sense only in surfactant systems, and generally not in single-component block copolymer hexagonal phases.

15       **Normal bicontinuous cubic phase:** The normal bicontinuous cubic phase is characterized by:

1. Small-angle x-ray shows peaks indexing to a three-dimensional space group with a cubic aspect. The most commonly encountered space groups, along with their indexings, are: Ia3d (#230), with indexing  $\sqrt{6}:\sqrt{8}:\sqrt{14}:4$ ; . . . ; Pn3m (#224), with indexing  $\sqrt{2}:\sqrt{3}:2:\sqrt{6}:\sqrt{8}$ ; . . . ; and Im3m (#229), with indexing  $\sqrt{2}:\sqrt{4}:\sqrt{6}:\sqrt{8}:\sqrt{10}$ ; . . . .
2. To the unaided eye, the phase is generally transparent when fully equilibrated, and thus often considerably clearer than any nearby lamellar phase.
3. In the polarizing optical microscope, the phase is non-birefringent, and therefore there are no optical textures.

25       For normal bicontinuous cubic phases in surfactant-water systems:

1. viscosity is high, much more viscous than the lamellar phase and even more viscous than typical normal hexagonal phases. Most cubic phase have viscosities in the millions of centipoise.
2. no splitting is observed in the NMR bandshape, only a single peak corresponding to isotropic motion.
3. in terms of phase behavior, the normal bicontinuous cubic phase generally

occurs at fairly high surfactant concentrations in single-tailed surfactant / water systems, typically on the order of 70% surfactant with ionic surfactants. Usually the normal bicontinuous cubic phase region is between lamellar and normal hexagonal phase regions, which along with its high viscosity and non-birefringence make its determination fairly simple. In double-tailed surfactants, it generally does not occur at all in the binary surfactant-water system.

For bicontinuous cubic phases in single-component block copolymer systems, the terms "normal" and "reversed" do not generally apply (although in the case where one block is polar and the other apolar, these qualifiers could be applied in principle). The shear modulus in such a bicontinuous cubic phase is generally much higher than a lamellar phase, and significantly than a hexagonal phase, in the same system. In terms of phase behavior, the bicontinuous cubic phases generally occur at volume fractions of the two blocks on the order of 26:74. In some cases, two bicontinuous cubic phases will straddle the lamellar phase, with, in each case, the minority component being inside the cylinders (this description replacing the 'normal/reversed' nomenclature of surfactant systems), and hexagonal phases straddling the cubic-lamellar-cubic progression.

**Reversed bicontinuous cubic phase:** The reversed bicontinuous cubic phase is characterized by:

In surfactant-water systems, the identification of the reversed bicontinuous cubic phase differs from the above identification of the normal bicontinuous cubic phase in only one respect. In terms of phase behavior, the reversed bicontinuous cubic phase is found between the lamellar phase and the reversed hexagonal phase, whereas the normal is found between the lamellar and normal hexagonal phases: one must therefore make reference to the discussion above for distinguishing normal hexagonal from reversed hexagonal. A good rule is that if the cubic phase lies to higher water concentrations than the lamellar phase, then it is normal, whereas if it lies to higher surfactant concentrations than the lamellar then it is reversed. The reversed cubic phase generally occurs at high surfactant concentrations in double-tailed surfactant / water systems, although this is often complicated by the fact that the reversed cubic phase may only be found in the presence of added hydrophobe ('oil') or amphiphile. The reversed bicontinuous cubic phase does appear in a number of binary systems with single-tailed surfactants, such as those of many monoglycerides (include glycerol monooleate), and a number of nonionic PEG-based surfactants with low HLB.

It should also be noted that in reversed bicontinuous cubic phases, though not in normal, the space group #212 has been observed. This phase is derived from that of space group #230. As stated above in the discussion of normal bicontinuous cubic phases, the distinction between 'normal' and 'reversed' bicontinuous cubic phases makes sense only in surfactant systems, and generally not in single-component block copolymer bicontinuous cubic phases.

**Normal discrete (non-bicontinuous) cubic phase:** The normal non-bicontinuous cubic phase is characterized by:

1. Small-angle x-ray shows peaks indexing to a three-dimensional space group

with a cubic aspect. The most commonly encountered space group in surfactant systems is Pm3n (#223), with indexing  $\sqrt{2}:\sqrt{4}:\sqrt{5}:\dots$ . In single-component block copolymers, the commonly observed space group is Im3m, corresponding to body-centered, sphere-packings, with indexing  $\sqrt{2}:\sqrt{4}:\sqrt{6}:\sqrt{8}:\dots$ .

2. To the unaided eye, the phase is generally transparent when fully equilibrated, and thus often considerably clearer than any associated lamellar phase.

3. In the polarizing optical microscope, the phase is non-birefringent, and therefore there are no optical textures.

For normal discrete cubic phases in surfactant-water systems:

1. viscosity is high, much more viscous than the lamellar phase and even more viscous than typical normal hexagonal phases. Most cubic phase have viscosities in the millions of centipoise, whether discrete or bicontinuous.

2. also in common with the bicontinuous cubic phases, there is no splitting in the NMR bandshape, only a single isotropic peak.

3. in terms of phase behavior, the normal discrete cubic phase generally occurs at fairly low surfactant concentrations in single-tailed surfactant / water systems, typically on the order of 40% surfactant with ionic surfactants. Usually the normal discrete cubic phase region is between normal micellar and normal hexagonal phase regions, which along with its high viscosity and non-birefringence make its determination fairly simple. In double-tailed surfactants, it generally does not occur at all in the binary surfactant-water system.

For discrete cubic phases in single-component block copolymer systems, the terms "normal" and "reversed" do not generally apply (although in the case where one block is polar and the other apolar, these qualifiers could be applied in principle). The shear modulus in such a

discrete cubic phase is generally dependent almost entirely on the shear modulus of the polymer that forms the blocks in the continuous phase. In terms of phase behavior, the discrete cubic phases generally occur at very low volume fractions of one or other of the two blocks, on the order of 20% or less.

5 **Reversed discrete cubic phase:** The reversed discrete cubic phase is characterized by: In surfactant-water systems, the identification of the reversed discrete cubic phase differs from the above identification of the normal discrete cubic phase in three respects:

10 1. In terms of phase behavior, the reversed discrete cubic phase is found between the lamellar phase and the reversed hexagonal phase, whereas the normal is found between the lamellar and normal hexagonal phases: one must therefore make reference to the discussion above for distinguishing normal hexagonal from reversed hexagonal. A good rule is that if the cubic phase lies to higher water concentrations than the lamellar phase, then it is normal, whereas if it lies to higher surfactant concentrations than the lamellar then it is reversed. The reversed cubic phase generally occurs at high surfactant concentrations in double-tailed surfactant / water systems, although this is often complicated by the fact that the reversed cubic phase may only be found in the presence of added hydrophobe ('oil') or amphiphile. The reversed discrete cubic phase does appear in a number of binary systems with single-tailed surfactants, such as those of many monoglycerides (include glycerol monooleate), and a number of nonionic PEG-based surfactants with low HLB.

15 2. The space group observed is usually Fd3m, #227.

20 3. The self-diffusion of the water is very low, while that of any hydrophobe present is high; that of the surfactant is generally fairly high, comparable to that in the lamellar phase.

25 As stated above in the discussion of normal discrete cubic phases, the distinction between 'normal' and 'reversed' discrete cubic phases makes sense only in surfactant systems, and generally not in single-component block copolymer discrete cubic phases.

**Intermediate phases:** The intermediate phase is characterized by:

These phases occur quite rarely, and when they are found they generally occupy very narrow regions in the phase diagram. Presently the structures of many of these are unknown or under debate. The intermediate phases can be classified as follows:

30 **Normal int(1) phases** occur at lower surfactant concentration than the normal

bicontinuous cubic phase, adjacent to the hexagonal phase. Viscosity is generally low or moderately low, no higher than that of the normal hexagonal phase. The phase is birefringent, with textures typically similar to those of the hexagonal phase. Self-diffusion of the components is very similar to those in the hexagonal phase. Small-angle x-ray shows a lower-symmetry space group than the cubic phases, typically monoclinic. Fairly sophisticated NMR bandshape and SAXS analyses can be used to distinguish this phase from the normal hexagonal phase. *See* Henriksson, U., Blackmore, E.S., Tiddy, G.J.T. and Soderman, O. (1992) *J. Phys. Chem.* 96:3894. Typically bandshape splittings will be intermediate between those of hexagonal and the zero splitting of the isotropic phase, which provides good evidence of an intermediate phase.

10       **Normal int(2)** is found at higher concentrations than the normal bicontinuous cubic phase, adjacent to the lamellar phase. These bear close resemblance, both in terms of property and probably also in terms of structure, to the normal bicontinuous cubic phases, except that they are birefringent, and show differences in NMR bandshape and SAXS analyses. Optical textures are somewhat unusual, in some cases resembling lamellar textures and in some resembling hexagonal, but these can be considerably coarser than either of the more common phases. As in the int(1) phases, the space group is of lower symmetry, typically rhombohedral or tetragonal, requiring two unit cell parameters for characterization, and making SAXS analysis difficult. In general, if the squares of the d-spacing ratios cannot be fit to a simple integral scheme, then an intermediate phase structure is suspect.

20       **Reversed int(2)** is found at lower concentrations than the reversed bicontinuous cubic phase, adjacent to the lamellar phase. These are birefringent, and show unusual in NMR bandshape and SAXS analyses. As in the int(1) and int(2) phases, the space group is of lower symmetry, typically rhombohedral or tetragonal, requiring two unit cell parameters for characterization, and making SAXS analysis difficult, SAXS analysis difficult, though the presence of Bragg peaks in the SAXS spectrum which do not index to a cubic or hexagonal lattice (which have only one lattice parameter) is, together with optical birefringence, indication of an intermediate phase. Space groups which are likely for bicontinuous intermediate phases have been discussed in a publication by the present author, D. M. Anderson, Supplement to *J. Physique. Proceedings of Workshop on Geometry and Interfaces, Aussois, France, Sept. 1990,*

25       C7-1 - C7-18.

At the time that the coated particle 10 is being formed and the exterior coating 20 is not

yet formed, it is highly desirable that the nanostructured liquid phase material or the nanostructured liquid crystalline phase material or the combination be one that is in equilibrium with water (polar solvent) or, more precisely, with a dilute aqueous solution. Once the coated particle 10 has its exterior coating 20, the foregoing nanostructured material need not be one that is in equilibrium with water. The liquid phases that can be in equilibrium with water are:

5 L2 phase (a.k.a. reversed micelles),

microemulsion, and

L3 phase (but not the L3\* phase).

These supplement the liquid crystalline phases that can be in equilibrium with water:

10 reversed cubic phase,

reversed hexagonal phase,

reversed intermediate phase, and

lamellar phase.

The phases that can be in equilibrium with water are preferred from the point of view of making

15 coated particles of the present invention. Preferably, in using the process described herein to disperse a given phase as the matrix, it is desirable that the phase be insoluble in water, or whatever solvent the particles are dispersed in. Furthermore, when the interior phase has the additional property that it is in equilibrium with excess aqueous solution during formation of the particles, then concerns of phase transformation are minimized. Similarly when the interior

20 phase is in equilibrium with excess aqueous solution under the conditions encountered when and after the particle coating is released, then the concerns of phase changes are likewise minimized. and in some applications this may be advantageous.

Whereas insolubility in water (external solvent, in general) is preferred for the matrix at the instant of particle formation, and frequently also at the time of application, there are

25 applications where solubility in water at the time of application is advantageous, and this can be accomplished with the instant invention. For example, consider a matrix composed of 20% C12E5 (pentaethylene glycol dodecyl ether) in water. At 75°C, this composition produces an L3 phase which is in equilibrium with excess water (dilute solution), and thus this composition would be readily dispersible at 75°C. If the application temperature were between 0 and 25°C, however, then this interior composition would be soluble in water, and in fact the C12E5 acts as an ordinary water-soluble surfactant at room temperature. This could be advantageous if a non greasy, non-comedogenic -- and even cleansing -- final product is desired after release of the

particle coating.

The nanostructured liquid phase material may be formed from:

- 5 a. a polar solvent and a surfactant or
- b. a polar solvent, a surfactant and an amphiphile or hydrophobe or
- c. a block copolymer or
- d. a block copolymer and a solvent.

The nanostructured liquid crystalline phase material may be formed from:

- a. a polar solvent and a surfactant,
- b. a polar solvent, a surfactant and an amphiphile or hydrophobe,
- 10 c. a block copolymer or
- d. a block copolymer and a solvent.

Above under the heading Chemical Criteria, criteria were discussed which could be used to select operative polar and apolar groups in order to make an operative surfactant. Thus, suitable surfactants include those compounds which contain two chemical moieties, one being an operative polar group chosen from those described in that discussion of polar groups, and the other being an operative apolar group chosen from those described in that discussion of apolar groups.

Suitable surfactants or block copolymer components (or mixtures thereof) may include:

- 20 a. cationic surfactant
- b. anionic surfactant
- c. semipolar surfactant
- c. zwitterionic surfactant
  - i. in particular, a phospholipid
  - 25 ii. a lipid mixture containing phospholipids, designed to match the physico-chemical characteristics of a biomembrane
- d. monoglyceride
- e. PEGylated surfactant
- f. one of the above but with aromatic ring
- 30 g. block copolymer
  - i. with both blocks hydrophobic, but mutually immiscible;
  - ii. with both blocks hydrophilic, but mutually immiscible;

iii. with one block hydrophilic and the other hydrophobic, i.e., amphiphilic)

h. a mixture of two or more of the above.

Suitable lipids include phospholipids (such as phosphatidylcholine, phosphatidylserine, 5 phosphatidylethanolamine, or sphingomyelin), or glycolipids (such as MGDG, diacylglycopyranosyl glycerols, and Lipid A.) Other suitable lipids are phospholipids (including phosphatidylcholines, phosphatidylinositols, phosphatidylglycerols, phosphatidic acids, phosphatidylserines, phosphatidylethanolamines, etc.), sphingolipids (including sphingomyelins), glycolipids (such as galactolipids such as MGDG and DGDG, 10 diacylglycopyranosyl glycerols, and Lipid A), salts of cholic acids and related acids such as deoxycholic acid, glycocholic acid, taurocholic acid, etc., gentiobiosyls, isoprenoids, ceramides, plasmalogens, cerebrosides (including sulphatides), gangliosides, cyclopentatriol lipids, dimethylaminopropane lipids, and lysolecithins and other lysolipids which are derived from the above by removal of one acyl chain.

15 Other suitable types of surfactants include anionic, cationic, zwitterionic, semipolar, PEGylated, and amine oxide. Preferred surfactants are:

anionic -- sodium oleate, sodium dodecyl sulfate, sodium diethylhexyl sulfosuccinate, sodium dimethylhexyl sulfosuccinate, sodium di-2-ethylacetate, sodium 2-ethylhexyl sulfate, sodium undecane-3-sulfate, sodium ethylphenylundecanoate, 20 carboxylate soaps of the form  $IC_n$  where the chain length n is between 8 and 20 and I is a monovalent counterion such as lithium, sodium, potassium, rubidium, etc.;

cationic -- dimethylammonium and trimethylammonium surfactants of chain length from 8 to 20 and with chloride, bromide or sulfate counterion, myristyl-gamma-picolinium chloride and relatives with alkyl chain lengths from 8 to 18, benzalkonium benzoate, double-tailed quaternary ammonium surfactants with chain lengths between 8 and 18 carbons and bromide, chloride or sulfate counterions;

30 nonionic PEGylated surfactants of the form  $C_nE_m$ , where the alkane chain length n is from 6 to 20 carbons and the average number of ethylene oxide groups m is from 2 to 80; ethoxylated cholesterol;

zwitterionics and semipolars -- N,N,N-trimethylaminodecanoimide, amine oxide

surfactants with alkyl chain length from 8 to 18 carbons; dodecyldimethylammoniopropane-1-sulfate, dodecyldimethylammoniobutyrate, dodecyltrimethylene di(ammonium chloride); decylmethylsulfonediimine; dimethyleicosylammoniohexanoate and relatives of these zwitterionics and 5 semipolars with alkyl chain lengths from 8 to 20.

Preferred surfactants which are FDA-approved as injectables include benzalkonium chloride, sodium deoxycholate, myristyl-gamma-picolinium chloride, Poloxamer 188, polyoxy 35 castor oil, sorbitan monopalmitate, and sodium 2-ethylhexanoic acid.

Suitable block copolymers are those composed of two or more mutually immiscible blocks from 10 the following classes of polymers: polydienes, polyallenes, polyacrylics and polymethacrylics (including polyacrylic acids, polymethacrylic acids, polyacrylates, polymethacrylates, polydisubstituted esters, polyacrylamides, polymethacrylamides, etc.), polyvinyl ethers, polyvinyl alcohols, polyacetals, polyvinyl ketones, polyvinylhalides, polyvinyl nitriles, polyvinyl esters, polystyrenes, polyphenylenes, polyoxides, polycarbonates, polyesters, polyanhydrides, 15 polyurethanes, polysulfonates, polysiloxanes, polysulfides, polysulfones, polyamides, polyhydrazides, polyureas, polycarbodiimides, polyphosphazenes, polysilanes, polysilazanes, polybenzoxazoles, polyoxadiazoles, polyoxadiazolidines, polythiazoles, polybenzothiazoles, polypyromellitimides, polyquinoxalines, polybenzimidazoles, polypiperazines, cellulose derivatives, alginic acid and its salts, chitin, chitosan, glycogen, heparin, pectin, polyphosphorus 20 nitrile chloride, polytri-n-butyl tin fluoride, polyphosphoryldimethylamide, poly-2,5-selenienylene, poly-4-n-butylpyridinium bromide, poly-2-N-methylpyridinium iodide, polyallylammonium chloride, and polysodium-sulfonate-trimethylene oxyethylene. Preferred polymer blocks are polyethylene oxide, polypropylene oxide, polybutadiene, polyisoprene, 25 polychlorobutadiene, polyacetylene, polyacrylic acid and its salts, polymethacrylic acid and its salts, polyitaconic acid and its salts, polymethylacrylate, polyethylacrylate, polybutylacrylate, polymethylmethacrylate, polypropylmethacrylate, poly-N-vinyl carbazole, polyacrylamide, polyisopropylacrylamide, polymethacrylamide, polyacrylonitrile, polyvinyl acetate, polyvinyl caprylate, polystyrene, poly-alpha-methylstyrene, polystyrene sulfonic acid and its salts, polybromostyrene, polybutyleneoxide, polyacrolein, polydimethylsiloxane, polyvinyl pyridine, 30 polyvinyl pyrrolidone, polyoxytetramethylene, polydimethylfulvene, polymethylphenylsiloxane, polycyclopentadienylene vinylene, polyalkylthiophene, polyalkyl-p-phenylene, polyethylene-alt-propylene, polynorbornene, poly-5-((trimethylsiloxy)methyl)norbornene, polythiophenylene.

heparin, pectin, chitin, chitosan, and alginic acid and its salts. Especially preferred block copolymers are polystyrene-*b*-butadiene, polystyrene-*b*-isoprene, polystyrene-*b*-styrenesulfonic acid, polyethyleneoxide-*b*-propyleneoxide, polystyrene-*b*-dimethylsiloxane, polyethyleneoxide-*b*-styrene, polynorbornene-*b*-5-((trimethylsiloxy)methyl)norbornene, polyacetylene-*b*-5-((trimethylsiloxy)methyl)norbornene, polyacetylene-*b*-norbornene, polyethyleneoxide-*b*-norbornene, polybutyleneoxide-*b*-ethyleneoxide, polyethyleneoxide-*b*-siloxane, and the triblock copolymer polyisoprene-*b*-styrene-*b*-2-vinylpyridine.

3. Third component: hydrophobe, or non-surfactant amphiphile
  - a. alkane or alkene, other long-chain aliphatic compound
  - b. aromatic compound, such as toluene
  - c. long-chain alcohol
  - d. a glyceride (diglyceride or triglyceride)
  - e. an acylated sorbitan, such as a sorbitan triester (e.g., sorbitan trioleate), or sesquioleate, or mixture of sorbitans with different numbers of acyl chains between 2 and 6
  - f. other hydrophobe or non-surfactant amphiphile or mixture with one or more of the above.
  - g. none.

Suitable third components (hydrophobes or non-surfactant amphiphiles), include: *n*-alkane, where *n* is from 6 to 20, including branched, unsaturated, and substituted variants (alkenes, chloroalkanes, etc.), cholesterol and related compounds, terpenes, diterpenes, triterpenes, fatty alcohols, fatty acids, aromatics, cyclohexanes, bicyclics such as naphthalenes and naphthols, quinolines and benzoquinolines, etc., tricyclics such as carbazole, phenothiazine, etc., pigments, chlorophyll, sterols, triglycerides, natural oil extracts (such as clove oil, anise oil, cinnamon oil, coriander oil, eucalyptus oil, peppermint oil), wax, bilirubin, bromine, iodine, hydrophobic and amphiphilic proteins and polypeptides (including gramicidin, casein, receptor proteins, lipid-anchored proteins, etc.), local anesthetics (such as butacaine, ecgonine, procaine, etc.), and low-molecular weight hydrophobic polymers (see listing of polymers above).

Especially preferred third components are: anise oil, clove oil, coriander oil, cinnamon oil, eucalyptus oil, peppermint oil, beeswax, benzoin, benzyl alcohol, benzyl benzoate, naphthol, capsaicin, cetearyl alcohol, cetyl alcohol, cinnamaldehyde, cocoa butter, coconut oil, cottonseed oil (hydrogenated), cyclohexane, cyclomethicone, dibutyl phthalate, dibutyl sebacate, dioctyl

phthalate, DIPAC, ethyl phthalate, ethyl vanillin, eugenol, fumaric acid, glyceryl distearate, menthol, methyl acrylate, methyl salicylate, myristyl alcohol, oleic acid, oleyl alcohol, benzyl chloride, paraffin, peanut oil, piperonal, rapeseed oil, rosin, sesame oil, sorbitan fatty acid esters, squalane, squalene, stearic acid, triacetin, trimyristin, vanillin, and vitamin E.

5 The polar solvent (or in the case of a block copolymer, the preferential solvent) may be:

- a. water
- b. glycerol
- c. formamide, N-methyl formamide, or dimethylformamide
- d. ethylene glycol or other polyhydric alcohol
- 10 e. ethylammonium nitrate
- f. other non-aqueous polar solvents, such as N-methyl sydnone, N-methyl acetamide, pyridinium chloride, etc.:
- 15 g. a mixture of two or more of the above.

Desirable polar solvents are water, glycerol, ethylene glycol, formamide, N-methyl 15 formamide, dimethylformamide, ethylammonium nitrate, and polyethylene glycol.

As previously stated, the exterior coating 20 may be formed of a nonlamellar crystalline material. The term "nonlamellar" as applied to crystal structure herein should be taken in the following context. Lamellar crystalline phases, which are distinct from lamellar liquid crystalline phases, occur in organic compounds (typically polar lipids), inorganic compounds, and 20 organometallics. Although these phases can be true crystalline materials and can thus exhibit long-range three-dimensional lattice ordering of the constituent atoms (or molecules, in the case of an organic crystalline material) in space, the forces and interactions between atoms—which can include covalent bonding, ionic bonding, hydrogen bonding, steric interactions, hydrophobic interactions, dispersion forces, etc.—are much stronger amongst the constituent atoms or 25 molecules that lie within the plane of a lamella than across distinct lamellae. For example, in the case of the layered structure of graphite, the atoms within a layer are covalently bonded with each other into a two-dimensional network, whereas between distinct layers there is no bonding, only the weaker dispersion forces and steric interactions. This absence of strong local 30 interlamellar interactions gives rise to a number of physicochemical properties which make them undesirable as coating materials in the present invention.

To begin with, the physical integrity of lamellar crystals is inherently compromised by the weak local interactions between layers. This is dramatically evidenced by the comparison

between graphite (a layered crystalline form of carbon) with diamond (a crystalline form of carbon that has three-dimensional bonding). Indeed, the fact that graphite is an important ingredient in certain lubricants, due to the ease with which the layers slide over each other, whereas diamond is an abrasive, illustrates the "liquid-like" (or "liquid crystal-like") character of 5 layered crystalline structures in terms of their response to shear. This same inter-lamellar sliding effect is, in fact, the same effect that gives rise to the much lower viscosity of the lamellar liquid crystalline phase compared with that of other liquid crystalline phases, in particular compared with the very high viscoelasticity of the bicontinuous cubic phase. As a further indication of this liquid-like nature, the Moh's hardness of graphite is 1.0, whereas that of diamond is 10. The loss 10 of integrity with shear in the case of graphite is seen in everyday life with "lead" pencils, which are graphite.

The detrimental effects associated with layered crystalline structures can be seen in everyday life even in situations where macroscopic shear is not involved. According to a widely-accepted model of the structure of emulsions advanced by Stig Friberg, as reviewed by 15 Larsson, K., and S. Friberg, Eds. 1990, Food Emulsions, 2<sup>nd</sup> Edition, Marcel Dekker, Inc. NY, lamellar liquid crystalline or, commonly, lamellar crystalline coatings stabilize the oil droplets in an oil-in-water emulsion, and the water droplets in a water-in-oil emulsion. In commonly encountered emulsions such as milk, ice cream, mayonnaise, etc., the instabilities that are well-known to the lay person -- and in the field referred to as "breaking" of emulsions -- are due in 20 large part to the fluidity of these layered coating materials. Even in a quiescent emulsion, these layered coatings undergo continual disruption, streaming, and coalescence, and with time any emulsion must ultimately succumb to the destabilizing effect of these disruptions.

And at yet another level, layered crystalline materials exhibit chemical instabilities of the type that would prevent their application as coatings in embodiments of the current invention. 25 Consider the case of the Werner complexes isomorphous to nickel dithiocyanate tetra(4-methylpyridine), that form clathrate compounds with a host lattice containing embedded guest molecules, in most cases yielding permanent pores upon removal of the guest. One such Werner complex was used as the coating in a particle in Example 22, thus illustrating the use of the present invention in creating particles with coatings possessing fixed, controlled-size and high- 30 selectivity pores. According to J. Lipkowski, Inclusion Compounds I, Academic Press, London (1984), p. 59: "Layered structures of  $\text{Ni}(\text{NCS})_2(4\text{-MePy})_4$  are stable only in the presence of guest molecules while the beta-phases preserve their porosity even in the absence of guest

molecules." The three-dimensional, non-layered structure of the beta-phases is discussed in detail in the same publication, such as: "... beta-phases... have a three-dimensional system of cavities interconnected through channels of molecular size".

The exterior coating 20 can protect the internal core 10 and any active agent(s) or component(s) disposed therein, for example, against oxidation, hydrolysis, premature release, precipitation, shear, vacuum, enzymatic attack, degradation from other components of the preparation, and/or conditions external to the coated particles, for example, in their preparation such as pH, ionic strength, or the presence of bioactive impurities, such as proteases or nucleases. Examples of each of these are:

10        **oxidation**: e.g., for antioxidants such as vitamin C, which are by their very nature sensitive to oxidation, or unsaturated lipids;

**hydrolysis**: e.g., for a drug with a labile ester bond;

**premature release**: e.g., during storage;

**precipitation**: e.g., for a drug in the protonated (hydrochloride) form that would deprotonate at the body pH and thereby become insoluble;

15        **shear**: e.g., in cases where processing after encapsulation endangers shear-sensitive compounds, such as proteins;

**vacuum**: e.g., in cases where processing involves vacuum-drying;

**enzymatic attack**: a peptide hormone, such as somatostatin, which is normally quickly digested by enzymes in the body, can be held active in circulation until reaching the site of release and action;

20        **degradation from other components**: e.g., where even a slight reactivity between a component disposed in the internal core and an exterior one could, over a shelf-life of months or years, pose a problem;

**external pH**: e.g., a drug in protonated form could be encapsulated at low internal pH to ensure solubility, but without requiring a low pH of the exterior liquid which would otherwise upset the stomach;

**external ionic strength**: e.g., where a protein is encapsulated to avoid salting-out and denaturation;

25        **external impurities such as proteases, nucleases, etc.**: e.g., when the exterior contains a bioreactor-derived product from which removal of proteases might be prohibitively expensive.

For the exterior coating 20, the nonlamellar crystalline material may be an organic compound, an inorganic compound, a mineral, a metal, such as gold, or other crystalline elemental form such as iodine, or an organometallic complex.

The structure of nonlamellar crystalline coating materials may be

5

- a. crystalline, non-porous
- b. crystalline with a one-dimensional network of pores
- c. crystalline with a two-dimensional network of pores
- d. crystalline with a three-dimensional network of pores

The coating may have the following surface charge characteristics:

10

- 1. Net cationic charge
  - a. under all conditions encountered in normal use or
  - b. under certain conditions as encountered at one or more stages of use
- 2. Net anionic charge
  - a. under all conditions encountered in normal use or
  - b. under certain conditions as encountered at one or more stages of use or
- 3. Uncharged:
  - a. at isoelectric point only or
  - b. over a pH range that spans the range of normal use or
  - c. in a pH range that is attained/induced during a stage of use (such as during collection of the particles via flocculation)

15

20

Examples of suitable nonlamellar crystalline coating materials, namely, compounds which occur in nonlamellar crystalline form over useful temperature ranges, and which are in most cases of low toxicity and environmental impact are:

25

30

ascorbic acid; ascorbic palmitate; aspartic acid; benzoin; beta-naphthol; bismuth subcarbonate; butylated hydroxytoluene; butylparaben; calcium acetate; calcium ascorbate; calcium carbonate; calcium chloride; calcium citrate; calcium hydroxide; calcium phosphate, dibasic; calcium phosphate, tribasic; calcium pyrophosphate; calcium salicylate; calcium silicate; calcium sulfate; carmine; cetearyl alcohol; cetyl alcohol; cinnamaldehyde; citric acid; cysteine hydrochloride; dibutyl sebacate; esculin; ferric oxide; ferric citrate; ferrosferric

oxide; gentisic acid; glutamic acid; glycine; gold; histidine; hydrochlorothiazide; iodine; iron oxide; lauryl sulfate; leucine; magnesium; magnesium aluminum silicate; magnesium carbonate; magnesium hydroxide; magnesium oxide; magnesium silicate; magnesium sulfate; magnesium trisilicate; maleic acid; malic acid, D,L-; methyl salicylate; methylparaben; monosodium glutamate; propyl gallate; propylparaben; silica; silicon; silicon dioxide; sodium aluminosilicate; sodium aminobenzoate; sodium benzoate; sodium bicarbonate; sodium bisulfate; sodium bisulfite; sodium carbonate; sodium chloride; sodium citrate; sodium metabisulfite; sodium nitrate; sodium phosphate, dibasic; sodium propionate; sodium salicylate; sodium stannate; sodium succinate; sodium sulfate; sodium sulfate; sodium thiosulfate; sodium thiosulfate; succinic acid; talc; talc triturate; tartaric acid; tartaric acid, DL-; tartrazine; tellurium; titanium dioxide; triacetin; triethyl citrate; trichloromonofluorethane; tromethamine and 2-hydroxy-n-cyclopropylmethyl morphinan hydrochloride; zinc oxide.

15 Calcium phosphate coatings are of interest in biomedical and pharmaceutical applications, since calcium phosphates are a major component of bone, teeth, and other structural components. For example, in the treatment of osteoporosis, the release of the appropriate pharmaceutical compound could be triggered by physiological conditions that induce dissolution of bone (and thus of the particle coating).

20 Potassium nitrate coatings are of interest in agricultural applications since the coating also act as plant fertilizers.

25 Iodine, aspartic acid, benzoic acid, butylated hydroxytoluene, calcium edetate disodium, gentisic acid, histidine, propyl gallate and zinc oxide can be particularly useful as crystalline coatings in potential pharmaceutical applications because they have relatively low water solubility (generally less than 5%) and are on the FDA list of approved inactive ingredients for injectable formulations.

Of particular interest as coating materials are clathrates. Examples of such materials are as follows:

30 1. Clathrates and inclusion compounds (some of which retain permanent porosity upon removal of the guest molecules):

Werner complexes of the form  $MX_2A_4$ , where M is a divalent cation (Fe, Co, Ni, Cu, Zn,

5 Cd, Mn, Hg, Cr), X is an anionic ligand (NCS<sup>-</sup>, NCO<sup>-</sup>, CN<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, Br<sup>-</sup>, I<sup>-</sup>), and A is an electrically neutral ligand-substituted pyridine, alpha-arylalkylamine or isoquinoline; examples of A include 4-methylpyridine, 3,5-dimethylpyridine, 4-phenylpyridine, and 4-vinylpyridine. A wide range of guest molecules can be included in these complexes, examples being benzene, toluene, xylene, dichlorobenzene, nitrotoluene, methanol, chloromethane, argon, krypton, xenon, oxygen, nitrogen, carbon dioxide, carbon disulfide, etc.

10 Reversible oxygen-carrying chelates such as bis-salicylaldehyde-ethylenediaminecobalt and other bis-salicylaldehyde-iminecobalt derivatives, cobalt(II) dihistidine and related cobalt(II) amino acid complexes, iron(II) dimethylglyoxime and nickel(II) dimethylglyoxime.

Complexes of the form K<sub>2</sub>Zn<sub>3</sub>[Fe(CN)<sub>6</sub>]<sub>2</sub>·xH<sub>2</sub>O, where certain values of the variable x correspond to complexes which yield permanent pores upon removal of the water.

## 2. Zeolites:

15 faujasite-type NaX zeolite  
faujasite-type NaY zeolite  
VPI-5 zeolite

20 The coated particles 1 of the present have application in a variety of fields. The coated particles 1 are adapted to absorb one or more materials from a selected environment, adsorb one or more materials from a selected environment or release one or more materials, such as active agents, disposed in the matrix.

With respect to absorption, the coated particles may be used to harvest products or scavenge waste in biological or chemical reaction processes, to carry catalysts in those processes, to remove toxins, antigens or waste products in medical applications, to identify a few examples.

25 With respect to adsorption, the coated particles may be used as chromatographic media and gas adsorbents.

With respect to release, the coated particles may be used for the controlled release of pharmaceutical agents, such as anticancer agents or photodynamic therapy agents, or cosmetic or

cosmeceutical materials. An active agent may be disposed in the matrix for release upon the triggering of release. For example, a pharmaceutical or biologically active material may be disposed in the matrix.

In applications of these microparticles in drug-delivery or with embedded proteins or 5 polypeptides (in particular receptor proteins), it can be highly advantageous to have an interior matrix which, although synthetic or semisynthetic, is designed to simulate closely the physiochemical properties of a natural biomembrane from a living cell. This could be important for the proper functioning of a receptor protein or other membrane component, for example, or for promoting assimilation of the interior matrix into the natural biomembrane in drug-delivery.

10 Physiochemical properties that can be important in such a context include the bilayer rigidity (a measure of the resistance to bending), bilayer fluidity (a measure of the microviscosity of the bilayer interior), the acyl chain length and bilayer thickness, the order parameter as a function of position on the lipid acyl chains, the surface charge density, the presence or absence of segregated lipid domains of differing composition within the bilayer, bilayer curvature and

15 monolayer curvature (for a discussion of the relationship between these two curvatures see H. Wennerström and D.M. Anderson, in Statistical Thermodynamics and Differential Geometry of Microstructured Materials, Eds. H.T. Davis and J.C.C. Nitsche, Springer-Verlag, 1992, p. 137), cholesterol content, carbohydrate content, and the lipid:protein ratio. By proper choice of composition, one can adjust these parameters to a large extent in an artificial system, namely a

20 nanostructured liquid phase or liquid crystalline phase. For example, the bilayer rigidity can be reduced by the addition of amphiphiles, particularly aliphatic alcohols; and bilayer charge can be adjusted by adjusting the ratio between uncharged lipids (such as phosphatidylcholine) and charged lipids (such as phosphatidic acid). Also, the addition of cholesterol is important for the function of a number of membrane proteins. The lamellar phase, the reversed bicontinuous cubic 25 phase, the L3 phase, and to a lesser extent the reversed hexagonal phase are in particular well-suited for this approach. Thus, a particle of the present invention, with the interior matrix being such a phase with tuned physiochemical characteristics for the functioning of incorporated proteins or other biomolecules, can be very valuable in products for pharmaceutics, clinical assays, biochemical research products, etc.

30 Membrane proteins are generally crucially dependent on a bilayer milieu in order to function properly and even to maintain proper conformation, and for such proteins the present invention – particularly with the bilayer properties tuned as described above – could be an

excellent and very useful matrix. Examples of membrane proteins include, in addition to receptor proteins, such proteins as proteinase A, amyloglucosidase, enkephalinase, dipeptidyl peptidase IV, gamma-glutamyl transferase, galactosidase, neuraminidase, alpha-mannosidase, cholinesterase, arylamidase, surfactin, ferrochelatase, spiralin, penicillin-binding proteins, 5 microsomal glycotransferases, kinases, bacterial outer membrane proteins, and histocompatibility antigens.

In view of the demanding requirements for the delivery of pharmaceuticals in the treatment of cancers, the advantages and flexibility of the present invention make it particularly attractive in the delivery and release of antineoplastic agents, such as for example, the following:

10 **ANTINEOPLASTICS**

**Alkylating Agents**

*Alkyl Sulfonates* - Busulfan. Imrosulfan. Piposulfan.

*Aziridines* - Benzodepa, Carboquone. Meturedopa. Uredopa,

*Ethylenimines and Methylmelamines* - Altretamine. Triethylenemelamine,

15 Triethylenephosphoramide. Triethylenethiophosphoramide. Trimethylolmelamine,

*Nitrogen Mustards* - Chlorambucil, Chlornaphazine, Cyclophosphamide, Estramustine, Ifosfamide, Mechlorethamine. Mechlorethamine Oxide Hydrochloride, Melphalan, Novembichin. Phenesterine. Prednimustine. Trofosfamide. Uracil Mustard,

*Nitrosoureas* - Carmustine, Chlorozotocin, Fotemustine, Lomustine, Nimustine. Ranimustine,

20 *Others* - Dacarbazine, Mannomustine. Mitobronitol, MitoLactol, Pipobroman,

**Antibiotics** - Actinomycins - Actinomycin Fl, Anthramycin, Azaserine, Bleomycins, Cactinomycin. Carubicin, Carzinophilin, Chromomycins, Dactinomycin, Daunorubicin, 6-Diazo-5-OXO-L-norieucine, Doxorubicin, Epirubicin, Mitomycins, Mycophenolic Acid, Nogalamycin, Olivomycins. Peplomycin, Plicamycin, Porfiromycin, Puromycin, Streptonigrin, Streptozocin, 25 Tubercidin, Ubenimex, Zinostatin, Zorubicin,

**Antimetabolites**

*Folic Acid Analogs* - Denopterin, Methotrexate, Pteropterin, Trimetrexate,

*Purine Analogs* - Fludarabine, 6-Mercaptopurine, Thiamiprine, Thioguanine,

*Pyrimidine Analogs* - Ancitabine, Azacitidine, 6-Azauridine, Carmofur, Cytarabine,

5 Doxifluridine, Enocitabine, Flouxuridine, Fluorouracil, Tegafur,

**Enzymes** - L-Asparaginase,

**Others** - Aceglatone. Amsacrine. Bestrabucil. Bisantrene. Carboplatin. Cisplatin. Defosfamide.

Demecolcine. Diaziquone. Eflornithine. Elliptinium Acetate. Etoposide. Gallium Nitrate, Hydroxyurea. Interferon- $\alpha$ , Interferon-P, Interferon- $\gamma$ . Interleukin-2, Lentinan,

10 Lonidamine. Mitoguazone, Mitoxantrone, Mopidamol, Nitracrine, Pentostatin, Phenamet, Pirarubicin, Podophyllinic Acid, 2-Ethylhydrazide, Procarbazine, PSK09. Razoxane, Sizofiran, Spirogermanium, Taxol, Teniposide, Tenuazonic Acid, Triaziquone. 2,2',211-Trichlorotriethylamine, Urethan, Vinblastine. Vincristine. Vindesine.

**ANTINEOPLASTIC (HORMONAL)**

15 **Androgens** - Calusterone. Dromostanolone Propionate. Epitiostanol. Mepitiostane. Testolactone.

**Antiadrenals** - Aminoglutethimide, Mitotane, Trilostane,

**Andandrogens** - Flutamide, Nilutamide,

**Antiestrogens** - Tamoxifen, Toremifene,

**Estrogens** - Fosfestrol. Hexestrol, Polyestradiol Phosphate,

20 **LH-RH Analogs** - Buserelin, Goserelin, Leuprolide, Triptorelin,

**Progestogens** - Chlormadinone Acetate, Medroxyprogesterone, Megestrol Acetate, Melengestrol,

#### **ANTINEOPLASTIC (RADIATION SOURCE)**

Americium, Cobalt, <sup>131</sup>I-Ethiodized Oil, Gold (Radioactive, Colloidal), Radium, Radon, 5 Sodium Iodide (Radioactive), Sodium Phosphate (Radioactive),

#### **ANTINEOPLASTIC ADJUNCTS**

**Folic Acid Replenisher** - Folinic Acid,

**Uroprotective** - Mesna.

Other examples of uses of coated particles of the present invention include:

- 10 1. Paints and inks, including Microencapsulation of pigments; Cationic charging of pigments (where pH-dependence can be important); Fillers and texturizing agents for non-aqueous paints;
2. Paper, including Microcapsular opacifiers (also in paints); Pressure-sensitive ink microcapsules for carbonless copying paper;
3. Non-wovens, including Additives that adhere to fibers throughout processing;
- 15 4. Agricultural, including Controlled release of pheromones (some of which are otherwise volatile or environmentally unstable if not encapsulated) for insect control; Controlled release of insect chemosterilants and growth regulators (many of which are otherwise environmentally unstable); Controlled release of other pesticides (with temperature independence being important); Controlled release of herbicides; Encapsulation of the plant growth regulators ethylene and acetylene (that are otherwise volatile); Taste modifiers to deter mammalian pests (e.g., capsaicin); Nutrient and fertilizer release;
- 20 5. Environment and forestry, including Controlled release of aquatic herbicides for weed

control; Controlled release of other herbicides; Controlled release of nutrients in mariculture; Soil treatment and nutrient release; Encapsulation and release of chelating agents (e.g., for heavy metal contaminants); Control of deposition and environmental fate of actives (viz.. through targeted release of crystal coating and/or adhesive property of cubic phase); Encapsulation of

5 hygroscopic or other (e.g., urea and sodium chloride) "seeding" agents for meteorological control;

6. Vaccines, including HIV gag, gag-pol transfection of cells as an example; Adjuvants for the proper presentation of antigens or antibodies;

7. Nuclear medicine, including Separation of two (otherwise mutually-destructive) radionuclides  
10 into separate particles for treatment of cancer:

8. Cosmetics, including Antioxidant, antiaging skin cream; Separation of two components of an antiacne medication; Suntan lotions with encapsulated prostaglandins and vitamins;

Encapsulation of fat-soluble vitamins, oxidatively sensitive vitamins, vitamin mixes;

Encapsulation of volatile perfumes and other odorants; Encapsulated volatile perfumes for

15 scratch and sniff advertisements; Encapsulation of volatile make-up removers or other cosmetics for sheet formation; Encapsulated solvents for nail polish removers (or the polish itself); Aerosol particles containing encapsulated hair dye; Sanitary napkins containing encapsulated deodorant;

9. Veterinary, including Controlled release of volatile anti-flea compounds; Encapsulated feed additives for ruminants; Encapsulation of anti-microbial and insecticides in animal husbandry;

20 10. Dental, including Controlled-release dentifrice components, particularly hydrolytically unstable anti-calculus compounds; Delivery of oral anti-cancer compounds (photophyrin);

11. Polymerization catalysts in one-pot (single-package) resin systems;

12. Household products, including Controlled-release air fresheners, perfumes; Controlled-release insect repellants; Laundry detergents (e.g., encapsulated proteases); Other detergency  
25 applications; Softeners; Fluorescent brighteners;

13. Industrial, including Encapsulation of phosphine, ethylene dibromide, etc. volatiles for fumigating stored products; Catalytic particles; Activated charcoal microparticles for sorption and purification;

14. Polymer additives, including Polymer additives for protection of wires, paper cartons etc. from rodents; Impact modifiers; Colorants and opacifiers; Flame retardant and smoke suppressants; Stabilizers; Optical brighteners;

Limitations in current polymer-based encapsulation of additives include low melting point (during processing), polymer-polymer incompatibility, particle size limitations, optical clarity, etc. Some polymer additives used for lubrication of the polymer are based on waxes, which suffer from very low melting point, except for certain synthetic waxes which are expensive.

15. Food and beverage processing, including Encapsulation of (volatile) flavors, aromas, and oils (e.g., coconut, peppermint); Encapsulation of vegetable fats in cattle feeds; Encapsulated enzymes for fermentation and purification (e.g., diacetyl reductase in beer brewing); Encapsulation as an alternative to blanching, for improved lifetime of frozen foods; Microencapsulated tobacco additives (flavorings); pH-triggered buffering agents; Removal of impurities and decolorization using activated charcoal encapsulated in a porous material;

16. Photographics, including Fine-grain film with dispersions of submicron photoreactive particles; Faster film due to optical clarity (and thus higher transmission) and shorter diffusion times of submicron dispersion; Microencapsulation of photoprocessing agents;

17. Explosives and propellants, including Both liquid and solid propellants and explosives are used in encapsulated form; also, water is used in encapsulated form as a temperature moderator in solid propellants;

18. Research, including Microcapsule-packed columns in extractions and separations; Biochemical assays, particularly in pharmaceutical research and screening;

19. Diagnostics, including Encapsulated markers for angiography and radiography and Clinical

assays involving milieu-sensitive proteins and glycolipids.

Desirable triggers for commencing the release of active agents, or alternatively commencing absorption, are:

1. Release is by dissolution or disruption of the coating

5 A. Intensive variable

1. pH
2. Ionic strength
3. Pressure
4. Temperature

10 B. Extensive variable or other

1. Dilution
2. Surfactant action
3. Enzymatic activity
4. Chemical reaction (non-enzymatic)
5. Complexation with target compound
6. Electric current
7. Irradiation
8. Time (i.e., slow dissolution)
9. Shear(critical shear rate effective)

20 II. Release or absorption is via pores in the coating, circumventing the need for the dissolution or disruption of the coating

1. Selective by pore size vs. compound size
2. Selective by pore wall polarity vs. compound polarity
3. Selective by pore wall ionicity vs. compound ionicity
4. Selective by pore shape vs. compound shape
5. Selective by virtue of the fact that some compounds or ions form porous inclusion compounds with the coating, whereas others do not (although this is generally a combination of the above 4 effects).

In a preferred embodiment, the coated particle may be made by

30 1. providing a volume of the matrix that includes at least one chemical species having a moiety capable of forming a nonlamellar crystalline material upon

reaction with a second moiety and

2. contacting the volume with a fluid containing at least one chemical species having the second moiety so as to react the first moiety with the second moiety and contemporaneously subdividing the volume into particles by the application of energy to the volume.

5 Alternatively, the coated particle can be made by

1. providing a volume of the matrix that includes the nonlamellar crystalline material in solution in it and
2. causing the nonlamellar crystalline material to become insoluble in the matrix and contemporaneously subdividing the volume into particles by the application of energy to the volume.

10 In the general method, a volume of the matrix is loaded with a compound A capable of forming a nonlamellar crystalline material on reaction with compound B, and a fluid (typically an aqueous solution, often referred to as the "upper solution") containing a compound B is overlaid on this,

15 and the contact between compound A and compound B induces crystallization at the interior/exterior interface, which coupled with the application of energy, such as sonication, causes particles coated with the nonlamellar crystalline material to break off into the fluid. This

method of the present invention is uniquely well-suited for producing aqueous dispersions of coated particles having coatings of materials with low water solubilities. i.e., preferably less than

20 about twenty (20) grams per liter of water and even more preferably less than about ten (10) grams per liter of water. It is highly advantageous in these processes for component A to be dissolved (i.e., not merely dispersed or suspended) in the matrix before the contact with B and

sonication begins, in order to obtain a homogeneous dispersion of microparticles in the end. As discussed above, this is one reason (in addition to requirements for optimizing solubilization of

25 actives, particularly biopharmaceuticals, in the matrix) for the importance of a nanostructured matrix having aqueous microdomains, in order to allow for the solubilization of compound A which in many cases is soluble only in polar solvents. In particular, reactions yielding

nonlamellar inorganic crystalline precipitates are generally performed most conveniently and effectively in aqueous media, and reactions yielding nonlamellar organic crystalline precipitates

30 from solubilized precursors are often most conveniently and effectively selected to be pH-induced protonation or deprotonation reactions of soluble salt forms of the desired nonlamellar

crystalline exterior coating material, where water (or an aqueous microdomain) is an obvious medium.

Alternatively, a cool temperature, or a crystallization promoter, or electric current, could be used to produce crystallization.

5 In addition to sonication, other standard emulsification methods could be used as energy inputs. These include microfluidization, valve homogenization [Thornberg, E. and Lundh, G. (1978) J. Food Sci. 43:1553] and blade stirring, etc. Desirably, a water-soluble surfactant, preferably an amphiphilic block copolymer of several thousand Dalton molecular weight, such as PLURONIC F68, is added to the aqueous solution in order to stabilize the coated particles  
10 against aggregation as they form. If sonication is used to promote particle formation, this surfactant also serves to enhance the effect of sonication.

Many of the nonlamellar crystalline material-coated particles described in the Examples reported herein were made by a process in which two or more reactants react to form a precipitate at the interface between the external solution and the nanostructured liquid or liquid 15 crystalline phase, and the precipitate forms the exterior coating. Another method which bears important similarities, as well as important differences, to this method is a general method in which the material that is to form the coating, call it material A, is dissolved in the liquid phase material or liquid crystalline phase material, with this dissolution being promoted by the change of one or more conditions in the material, such as an increase in temperature (but it could be  
20 another change such as decrease in pressure, addition of a volatile solvent, etc.) This change must be reversible, so that upon reversal of the condition -- decrease of the temperature, increase in pressure, evaporation of solvent, etc. -- the system reverts to a two-phase mixture of a nanostructured liquid or liquid crystalline phase material and a nonlamellar crystalline material A. Energy input is applied before the nonlamellar crystalline material A has the time to coarsen  
25 into large crystals, where this may be through the application of ultrasound, or other emulsification methodology. This causes the breaking off of particles coated with nonlamellar crystalline material A.

For the case where temperature is used, the solubility of compound A in the nanostructured liquid phase material or nanostructured liquid crystalline phase material must 30 change with temperature, and the higher the magnitude of the slope of the solubility versus temperature plot, the smaller the temperature increment needed to perform this process. For example, the solubility of potassium nitrate in water is a very strong function of temperature.

A fundamental difference between the precipitation reaction process and this type of process is that in this type of process, only one compound (A) is needed in addition to the nanostructured interior matrix. In the precipitation reaction method, at least two compounds are needed, component A which is in the nanostructured phase, and component B which starts out in the exterior phase ("upper solution") which is overlaid on top of the nanostructured phase. Component B in that case is often simply a suitably chosen acidic or basic component. This serves to point out a similarity between the two processes, in that the presence of component B in the exterior phase can alternatively be thought of as a "condition" (in particular, pH in the acid/base case) which causes the crystallization of A; that is, A may be solubilized by the use of basic pH, and this is reversible by the use of acidic pH conditions, which are applied by the presence of the exterior phase. Probably the most important distinction between the two methods is whether the change in conditions that causes the crystallization of A occurs only when and where the exterior phase ("upper solution") contacts the nanostructured phase, as in the A/B precipitation reaction, or whether it is occurring simultaneously throughout the bulk of the nanostructured phase, as in the temperature-induced crystallization.

It is also possible to use a process which is a combination of the A/B reaction process and the temperature process described above. Typically in such a scheme, the compound desired as the particle coating would be added to the matrix in two chemical forms. The first would be the chemical form of the final coating, typically the free acid (free base) form of a compound, which would be soluble only at elevated temperature and insoluble in the matrix at the temperature of particle formation. The second would be a precursor form, typically the salt form made by reacting the free acid with a base such as sodium hydroxide (or reacting the free base form with an acid such as hydrochloric acid), where this precursor form would be soluble in the matrix even at the temperature of particle formation. For example, for the case of a benzoic acid particle coating, both benzoic acid and sodium benzoate would be added to the matrix, where the matrix is such that it does not dissolve benzoic acid at ambient temperature, but does at a higher temperature. The upper solution would contain the necessary component(s) to convert the precursor form to the final coating form, such as hydrochloric acid in the case of sodium benzoate. Upon heating (so that both forms are substantially dissolved), and then cooling, overlaying the upper solution, and sonicating or otherwise adding energy to the system, the formation of coated particles would involve the two methods of cooling-induced precipitation and reaction-mediated formation and precipitation of coating crystal. This could have

advantages, in terms of providing two sources of crystalline coating material that could result in particle coverage at an earlier stage than with either method separately, thus providing added protection against particle fusion (and possibly leading to a more uniform particle size distribution), and more efficient particle formation with less energy input requirement, etc.

5 Other methods that may be used for making coated particles of the present invention are:

- A. ElectrocrySTALLIZATION,
- B. Seeding (with supersaturated solution in matrix, seed in exterior phase),
- C. Promotion (with supersaturated solution in one phase, crystallization promoter in the other phase),
- 10 D. Inhibition removal (with supersaturated solution in one phase and seed in the other phase). or
- E. Time method (crystals grow slowly from supersaturated solution in interior phase.)

In order to form many of the desired exterior coatings, including nearly all of the inorganic ones, one of the reactants (and usually both) will inevitably be soluble only in water, or 15 other polar solvent. In particular, most of the salts that are used in these precipitation reactions will dissolve only in highly polar solvents. At the same time, in order for a matrix material to be dispersible in water in accordance with the present invention, it appears to be a highly desirable, if not an absolute, condition that the interior phase material not be of substantial solubility in water, otherwise some or all of the material will dissolve in the upper solution rather than be 20 dispersed in it. Therefore, in order to form these coatings, the matrix must satisfy two conditions:

condition 1: it must contain aqueous(or other polar solvent) domains; and

condition 2: it must be of low solubility in water, i.e., sufficiently low (or with 25 sufficiently slow dissolution kinetics) that substantial dissolution of the phase does not occur during the process of particle production from the phase (typically 5 to 100 minutes to disperse the entire material into particles), since this would substantially reduce the yield efficiency and could thus diminish the overall attractiveness of the method.

These two conditions are working in nearly opposite directions, and very few systems can be found that will satisfy both. Nanostructured liquid phase materials and liquid crystalline phase 30 materials, of the reversed type or the lamellar type, are several of these very few systems.

In some cases, it will be advantageous to incorporate into the upper solution one or more of the components that are in the nanostructured liquid or liquid crystalline phase, and at times in

appreciable amounts. Indeed, there are instances when it may be advantageous to have a nanostructured, surfactant-rich liquid phase for the upper solution. In particular, this could occur when the matrix phase is not in equilibrium with water (or a dilute aqueous solution), but is in equilibrium with another liquid or liquid crystalline phase, such as a micellar phase or even a 5 low-viscosity lamellar phase. Thus, as the "fluid" referred to in the general description of the process given above, one could use such a phase, or such a phase to which additional components, such as reactant B and/or amphiphilic block copolymer stabilizer, have been added. In this case there might well be no complications introduced by any incorporation of this upper 10 phase into the microparticles, should that occur, since the upper phase could be (and generally would be) chosen so as to be in equilibrium with the matrix phase (except possibly for exchange of the active ingredient between the two materials, which would have some consequences but these would often be relatively unimportant). After formation of the coated particles, which would originally be dispersed in this upper "solution", through the use of filtration or dialysis the continuous outer phase could be changed from this to another medium, such as water, saline, 15 buffer, etc.

The following examples illustrate the present invention but are not to be construed as limiting the invention.

### **EXAMPLES**

In the following examples, Examples 14, 15, 16, and 34 demonstrate systems with 20 coatings made of physically robust mineral materials, such as cupric ferrocyanide and calcium phosphate, that can provide for stability of the intact particles under stronger shear conditions, such as during pumping of a dispersion of the coated particles, for example, for recycling or transport. These minerals are also of low aqueous solubility, making them of potential interest in applications requiring release of the particle coating by strong shear, while at the same time 25 protecting against release due to simple dilution with water. An example of such an application would be where a rodent deterrent such as capsaicin, or rodent toxin, would be encapsulated in the coated particles of the present invention, the particles impregnated into electrical wires, corrugated boxes, and other products requiring protection against gnawing by rodents, and the gnawing action of a rodent would induce release of the active deterrent or toxin. The low water 30 solubility would prevent the deterrent from premature release due to damp conditions.

A robust organic material that provides a coating that is also of low aqueous solubility is

ethylhydrocupreine, as in examples 17 and 33, and this compound has the additional characteristic that it has an extremely bitter taste that could provide an additional deterrent effect in a rodent-deterrant application.

Examples 1, 2, 3, 6, 7, 8, 9, 10, 17, 18, 19, 20, 23 and 33 provide examples of coatings 5 that are of low water solubility at neutral pH, but that increase substantially in solubility as the pH becomes either acidic or basic, depending on the compound. This can make the coated particles of importance in, for example, drug delivery, where a coating that releases preferentially in a particular pH range is desired, such as for intestinal release. Or such a coating could release, allowing the release of an antibacterial compound, at sites of bacterial activity, where pH is 10 typically acidic. Or the release of the coating at a particular pH could allow the release of a pH-stabilizing compound or a buffer system, for example in microparticles designed to control the pH of water in swimming pools.

Example 4 gives an example of particles with a coating, silver iodide, that could provide 15 very useful properties as a cloud-seeding agent, since the silver iodide coating is well-known for cloud-seeding effectiveness, and the surface area and surface morphology afforded by the particle shape and size could amplify the effect of the silver iodide. This could be of commercial importance due to the expense of silver compounds, in which case the inexpensive liquid crystal interior could serve the role as a filler that would provide the same or greater seeding potential at a fraction of the cost of simple silver iodide. A similar increase in effectiveness due to 20 amplification of surface area might prove of interest in the use of the particles as local anesthetics for mucous membranes, and the proper balance of lipids and active anesthetic hydrophobes (such as lidocaine) in the particle interior could be used to enhance the effect.

Example 5 demonstrates that compounds such as sulfides and oxides can be used as 25 coatings in the coated particles of the present invention, even when they require gaseous reactants for formation. Such compounds are well-known for being not only high-stiffness materials, but also chemically extremely resistant, which could make such coated particles of interest in applications where the particles encounter harsh chemical and physical conditions, such as would be expected in use of the particles as polymer additives, or in processing involving high shear, such as impregnation of dye-containing particles in nonwoven materials, etc.

Examples 12 and 13 demonstrate the use of high water-solubility compounds as coatings, 30 that can be of importance in applications requiring quick and convenient release of the coating by simple dilution with water. For instance, a spray system that would merge two streams, one

containing the dispersion and the other water, could provide an aerosol in which the particle coating, useful for preventing agglomeration prior to spraying, would be dissolved after spraying when the particles were already aerosolized -- in flight, so to speak. Since this dissolution could expose, for example, a nanostructured cubic phase interior that was very tacky, the particles 5 could be used to adhere to, e.g., crops, or the bronchial lining, etc. The capsaicin loaded into the interior in Examples 12 and 13 would make this product of potential importance in providing rodent resistance after deposition of the tacky aerosolized particles onto crops, for example, since rodents are generally strongly repelled by the taste of capsaicin even at very low concentrations.

All percentages in the following examples are weight percentages unless otherwise noted. 10 The amounts of the components used in the following examples can be varied as desired, provided that the relative amounts remain as in the example; thus, these amounts can be scaled proportionately to the desired amount, recognizing of course that scaling up to large amounts will require larger equipment to process.

In the following examples, unless otherwise noted, the exterior coating of each coated 15 particle comprises a nonlamellar crystalline material and each interior core comprises a matrix consisting essentially of at least one nanostructured liquid phase, at least one nanostructured liquid crystalline phase or a combination of at least one nanostructured liquid phase and at least one nanostructured liquid crystalline phase.

#### EXAMPLE 1

20 This Example shows that a wide range of active compounds, including compounds of importance in pharmaceutics and biotechnology, can be incorporated into nonlamellar crystalline material-coated particles of the present invention

An amount of 0.266 grams of sodium hydroxide was dissolved in 20 ml of glycerol, 25 using heating and stirring to aid in dissolution. An equimolar amount, namely 1.01 grams, of methyl paraben was then dissolved, again with heating. From this solution, 0.616 grams were taken out and mixed with 0.436 grams of lecithin and 0.173 grams of oleyl alcohol in a test tube. The active ingredient (or agent) identified below was incorporated at this point and the solution thoroughly mixed to form a nanostructured liquid crystalline phase material with an active ingredient disposed within it. An "upper solution", which was obtained by dissolving 0.062 30 grams of PLURONIC F-68 (a polypropyleneoxide-polyethyleneoxide block copolymer surfactant commercially available from BASF) and 0.0132 grams of acetic acid together and

adding to the test tube as a layer of solution above the previous solution that included the active agent. Immediately the test tube containing the liquid crystalline mixture and the upper solution was shaken vigorously and sonicated for three hours in a small, table-top ultrasonicator (Model FS6, manufactured by Fisher Scientific.) The resulting dispersion showed a high loading of 5 particles coated with methyl paraben with size on the order of one micron upon examination with an optical microscope.

Example 1A 2.0 wt% of salicylic acid (based on the weight of the internal core of liquid crystalline phase material) was incorporated as an active agent.

Example 1B 2.0 wt% Vinblastine sulfate (based on the weight of the internal core of liquid 10 crystalline phase material) was incorporated as an active agent.

Example 1C 2.4 wt% Thymidine (based on the weight of the internal core of liquid crystalline phase material) was incorporated as an active agent.

Example 1D 1.6 wt% Thyrotropic hormone (based on the weight of the internal core of liquid 15 crystalline phase material) was incorporated as an active agent.

Example 1E 2.9 wt % Anti 3', 5' cyclic AMP antibody (based on the weight of the internal core of liquid crystalline phase material) was incorporated as an active agent.

Example 1F 2.0 wt% L-Thyroxine (based on the weight of the internal core of liquid crystalline phase material) was incorporated as an active.

Particles such as these with a coating which increases substantially in solubility as the pH 20 increases, could be useful in drug delivery, where the increase in pH moving along the gastrointestinal tract from the stomach to the intestines could result in effective delivery to the lower gastrointestinal tract, giving rise to a more uniform delivery rate over time.

## EXAMPLE 2

This example demonstrates the long-term stability of a dispersion of particles of the 25 present invention.

The amino acid D,L-leucine, in the amount of 0.132 grams, was dissolved in 2.514 grams of 1M hydrochloric acid, resulting in the formation of leucine hydrochloride in solution. The solution was dried on a hot plate under flow of air, but was not allowed to dry to complete dryness; drying was stopped when the weight reached 0.1666 gram, which corresponds to one 30 molar equivalent addition of HCl to the leucine. An amount of 0.130 grams of this compound were added to 0.879 grams of a nanostructured reverse bicontinuous cubic phase material

prepared by mixing sunflower oil monoglycerides and water, centrifuging, and removing the excess water. An upper solution was prepared by mixing 1.0 grams of 1M sodium hydroxide with 3 grams of water. All water used was triply-distilled. The upper solution was overlaid on the cubic phase, the test tube sealed and sonicated, resulting in the formation of a milky-white dispersion of microparticles coated with leucine.

A similar dispersion was prepared with the use of PLURONIC F-68 as stabilizer. An amount of 0.152 grams of leucine hydrochloride was added to 0.852 grams of nanostructured reverse bicontinuous cubic phase material as above, and an upper phase consisting of 0.08 grams of F-68, 1.0 gram of 1M sodium hydroxide, and 3.0 grams of water was overlaid on the nanostructured reverse bicontinuous cubic phase material and sonicated. Again, a milky-white dispersion of leucine-coated microparticles was formed, where this time the F-68 amphiphilic block copolymer surfactant coated the outer (leucine-based) surface of the particles.

As a control experiment to show the necessity of the leucine for the formation of crystal-coated particles, 1.107 grams of DIMODAN LS (hereinafter "sunflower monoglycerides") were mixed with 1.000 gram of water to form a nanostructured reverse bicontinuous cubic phase material. An upper solution was prepared by adding 0.08 grams of PLURONIC F-68 to 4.00 grams of water. As per the same procedure used to make the dispersions above using leucine, the upper solution was overlaid on the nanostructured reverse bicontinuous cubic phase material and the test tube sealed and sonicated. In this case, essentially no microparticles were formed: the nanostructured reverse bicontinuous cubic phase material remained as large, macroscopic chunks even after several hours of sonication under the same conditions as the leucine experiment.

This dispersion of the coated particles of the present invention was examined regularly for a period of twelve months and did not show signs of irreversible flocculation. With even slight agitation, it showed no signs of irreversible flocculation over time scales of weeks. In the absence of agitation, it did show signs of flocculation, but upon mild shaking for 5 seconds or more, any flocculation reversed. A droplet of the dispersion was examined in an Edge Scientific R400 3-D microscope at 1,000 magnification (100x objective, oil immersion, transmitted light) and shown to have a very high loading of submicron particles.

Particles such as these, with relatively weak organic coatings, can be used, for example, in acne creams, where an active material such as triclosan could be incorporated and the shear associated with applying the material to the skin would release the coating.

EXAMPLE 3

In this example paclitaxel was incorporated at the level of 0.5% of the internal core. The particle coating was leucine, which in other examples herein has been shown to provide long-term stability.

5 A paclitaxel-containing nanostructured reverse bicontinuous cubic phase material was produced by mixing 4 mg of paclitaxel, dissolved in 2 ml t-butanol, in a nanostructured reverse bicontinuous cubic phase material containing 0.280 gm lecithin, 0.091 gm of oleyl alcohol, and 0.390 gm glycerol; after evaporation of the butanol under argon, a nanostructured reverse bicontinuous cubic phase material formed that was viscous and optically isotropic. The sample  
10 was centrifuged for one hour, during which time no precipitate appeared. Optical isotropy was verified in a polarizing optical microscope. A leucine hydrochloride solution in glycerol was produced by mixing 0.241 grams of leucine, 2.573 grams of 1M HCl, and 0.970 grams of glycerol, after which the water and excess HCl were evaporated under air flow on a 50°C hot plate, drying for three hours. Next, 0.882 grams of this leucine-HCl in glycerol solution were  
15 added to the nanostructured reverse bicontinuous cubic phase material. The upper solution was then prepared by adding 0.102 grams of PLURONIC F-68 to 4.42 grams of an aqueous buffer at pH 5.0. After overlaying the upper solution onto the nanostructured reverse bicontinuous cubic phase material, the nanostructured reverse bicontinuous cubic phase material was dispersed into microparticles by sonicating for 2 hours.

20 Particles such as these could be used for the controlled release of the antineoplastic agent paclitaxel.

EXAMPLE 4

In this example, the coating was silver iodide, which has the potential to make the particles useful in photographic processes. Silver iodide is somewhat unusual in that, even  
25 though it is a simple salt (with monovalent ions only), it has a very low solubility in water.

A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.509 grams of DIMODAN LS (commercially available as from Grinstedt AB and referred to herein as "sunflower monoglycerides"), 0.563 grams of triply-distilled water, and 0.060 grams of sodium iodide. An upper solution was prepared by adding 0.220 grams of silver nitrate, 0.094 grams of PLURONIC F-68, and 0.008 grams of cetylpyridinium chloride to 3.01 grams of water.  
30 A dispersion of microparticles was then produced by overlaying the upper solution onto the

nanostructured reverse bicontinuous cubic phase material and sonicating for one hour. The particle coating was silver iodide, which has a low solubility in water.

#### EXAMPLE 5

In this example cadmium sulfide was used as the coating. It is a nonlamellar crystalline compound that exhibits large changes in physical properties when doped with small amounts of other ions. This example also demonstrates that a gas, such as hydrogen sulfide gas, can be used in the present invention to induce crystallization and particle formation.

A nanostructured reverse bicontinuous cubic phase material was prepared by thoroughly mixing 0.641 grams of DIMODAN LS with 0.412 grams of water, and to this was added 0.058 grams of cadmium sulfate hydrate. After this, 0.039 grams of calcium sulfide was overlaid on the mixture, and the test tube was purged with argon gas and capped. An upper solution was prepared by adding 0.088 grams of PLURONIC F-68 and 1.53 grams of glycerol to 1.51 grams of 1M HCl, and then sparging the solution with argon. The upper solution was taken up in a syringe, and added to the first test tube. Upon addition, the smell of hydrogen sulfide gas could be detected in the test tube, as well as the formation of a yellowish precipitate; this indicated the action of hydrogen sulfide gas in producing cadmium sulfide (CdS) from the cadmium sulfate. The system was sonicated, resulting in a dispersion of microparticles which had a cadmium sulfide coating.

#### EXAMPLE 6

This example demonstrates that the interior is substantially protected from contact with conditions outside the particle by the crystalline coating, which here is leucine. Any contact with zinc dust changes methylene blue to colorless in less than one second; here, addition of zinc did not cause a loss of color for some 24 hours. Although there was an eventual loss of color, that loss is believed to be due simply to the effect of the zinc on the leucine coating.

A solution of leucine hydrochloride in water was made by mixing 0.122 grams of leucine with 1.179 grams of 1M HCl, and evaporating until approximately 1 gram of solution remained. To this was added 0.922 grams of sunflower monoglycerides, and 10 drops of a strongly colored aqueous solution of methylene blue. An upper solution was produced by adding 0.497 grams of 1M NaOH and 0.037 grams of PLURONIC F-68 to 3.00 grams of pH 5 buffer. The upper solution was overlaid, the system sonicated, and a dispersion of microparticles formed. An

aliquot of the dispersion was filtered to remove any undispersed liquid crystal, and 0.1 grams of 100 mesh zinc dust added. (When zinc dust is shaken with a solution of methylene blue, the reducing effect of the zinc removes the blue color, normally in a matter of a second, or almost instantaneously.) However, in the case of the microencapsulated methylene blue produced by this process, it took on the order of 24 hours for the color to disappear, finally resulting in a white dispersion. Thus, despite interactions between the zinc and the leucine that can disrupt the coatings of these particles, the coatings provided substantial protection of the methylene blue against the effect of the zinc, increasing the time required for zinc reduction of the dye some 4-5 orders of magnitude.

If particles such as these are employed in a product in which two active ingredients must be sequestered from contact with each other (such as the oxidation-sensitive antibacterial compound triclosan and the strongly oxidizing cleansing agent benzoyl peroxide), this experiment demonstrates the feasibility of using leucine-coated particles in preventing contact between an encapsulated compound and the environment outside the particle.

15

#### EXAMPLE 7

In this example a leucine coating protects the methylene blue dye in the particle interior from contact with ferrous chloride, as easily seen by the absence of the expected color change when ferrous chloride is added to the dispersion. This indicated that the coating was substantially impermeable even to ions.

20

A solution of leucine hydrochloride in glycerol was made by mixing 0.242 grams of leucine, 2.60 grams of 1M HCl, and 1.04 grams of glycerol, and then drying on a 50° C hot plate under flow of air for 1.5 hours. A nanostructured reverse bicontinuous cubic phase material was prepared by mixing this leucine-HCl solution, 0.291 grams of lecithin (EPIKURON 200, from Lucas-Meyer), 0.116 grams of oleyl alcohol, and 0.873 grams of glycerol; this was colored by the addition of a pinch of methylene blue. An upper solution was prepared by adding 0.042 grams of PLURONIC F-68 surfactant to 4.36 grams of pH 5 buffer, overlaid on the nanostructured reverse bicontinuous cubic phase material, and the system sonicated to produce a dispersion of microparticles. To an aliquot of this dispersion was added 0.19 grams of ferrous chloride, a reducing agent. The absence of a color change indicated that the methylene blue was protected against contact with the ferrous compound by encapsulation in the leucine-coated particles, since the addition of ferrous chloride to methylene blue solutions normally changes the

color to blue-green (turquoise).

Similarly to Example 6, this experiment shows that encapsulated compounds such as methylene blue which are sensitive to, in this case, reducing agents, can be protected against reducing conditions outside the particle until release of the coating. This could be useful in, for example, electrochemical applications where the effect of application of electrical current would be gated by the chemical release of the coating.

#### EXAMPLE 8

This example, when considered along with Example 1A and Example 10, demonstrates that particles of the present invention coated with methyl paraben can be produced in two entirely different ways: either by a thermal process, such as a heating-cooling method, or by a chemical reaction, such as an acid-base method.

To a nanostructured reverse bicontinuous cubic phase material, produced by mixing 0.426 grams of sunflower monoglycerides (DIMODAN LS) with 0.206 grams of acidic water at pH 3, were added 0.051 grams of methyl paraben and a trace of methylene blue dye. The mixture was heated to 110°C, shaken and put on a vibro-mixer, and plunged into 23°C water for 5 minutes. Two milliliters of a 2% PLURONIC F-68 solution, acidified to pH 3 with HCl, were overlaid, the test tube sealed with a twist cap, and the tube shaken and then sonicated for 30 minutes. This produced a dispersion of microparticles coated with methylparaben.

Since this experiment along with Example 10 demonstrate that particles coated with the same compound, in this case methyl paraben, can be produced either by a thermal method or by a chemical precipitation method, this provides an extra degree of versatility which can be important in optimizing production efficiency and minimizing costs, for example in large-scale pharmaceutical production of microencapsulated drugs.

#### EXAMPLE 9

The nanostructured reverse bicontinuous cubic phase material in this example is based on nonionic surfactants, which are generally approved for drug formulation, and which yield liquid crystalline phase materials with properties tunable by small temperature changes. For example, in an acne cream this could be used to achieve detergent (cleansing) properties at the temperature of application, but insolubility at the temperature of formulation. Furthermore, since it is based on a tuned mixture of two surfactants, and since the phase and properties thereof depend

sensitively on the ratio of the two surfactants, this provides a convenient and powerful means to control the properties of the internal core. In addition, this example resulted in a transparent dispersion. This is noteworthy because even a small fraction of particles with a size larger than about 0.5 microns gives rise to an opaque dispersion.

5 A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.276 grams of "OE2" (an ethoxylated alcohol surfactant commercially available as "Ameroxol OE-2", supplied by Amerchol, a division of CPC International, Inc.) with 0.238 grams of "OE5" (an ethoxylated alcohol surfactant commercially available as "Ameroxol OE-2", supplied by Amerchol, a division of CPC International, Inc.), and adding 0.250 grams of water (includes 10 excess water). To this was added 0.054 grams of methyl paraben and a trace of methylene blue dye. The mixture was heated to 110° C, shaken and put on a vibro-mixer, and plunged into 23 C water for 5 minutes. Two milliliters of a 2% PLURONIC F-68 solution, acidified to pH 3 with HCl, were overlaid, the test tube sealed with a twist cap, and the tube shaken and then sonicated for 30 minutes. This produced a dispersion of microparticles coated with methylparaben.

15 Interestingly, the sub-micron size of the particles resulted in a transparent dispersion.

#### EXAMPLE 10

This example shows that methyl paraben-coated particles can be created by a heating-cooling process, in addition to the acid-base method of the previous example. This example also demonstrates that a mixture of two phases can be dispersed.

20 Lecithin (EPIKURON 200, 0.418 grams) was mixed with 0.234 grams of oleyl alcohol and 0.461 grams of acidic water at pH 3, resulting in a mixture of nanostructured reverse bicontinuous cubic phase material and nanostructured reversed hexagonal phase material. Out of this was taken 0.50 grams, to which were added 0.049 grams of methyl paraben, and mixed well. This was heated to 120°C, stirred while hot, then reheated to 120°C. The test tube was removed 25 from the oven, and the test tube plunged into cold water for 5 minutes. After this the twist-cap was taken off, two milliliters of a 2% PLURONIC F-68 solution, acidified to pH 3 with HCl, were overlaid, and the sample stirred, shaken, and finally sonicated. This resulted in a milky-white dispersion of microparticles coated with methyl paraben. Examination in an optical microscope showed microparticles with sizes in the range of 2-10 microns. Excess methyl 30 paraben crystalline material was also seen.

This example demonstrates that a mixture of two co-existing nanostructured phases can

provide the interior of the microparticles. This could be important in, for example, controlled-release drug delivery, where a mixture of two phases, each loaded with drug, could be used to achieve a desired pharmacokinetics: for example, with a mixture of a reversed hexagonal phase and a cubic phase, the release from these two phases follows different kinetics, due to the 5 different geometry of the porespaces, and the resulting kinetics would be a combination of these two profiles.

#### EXAMPLE 11

This example shows that water-free particle interiors can be produced, such as for protection of water-sensitive compounds.

10 The same procedure used in the preparation of Example 10 was used, but the water was replaced by glycerol (which was present in excess) in the preparation of the nanostructured bicontinuous reversed cubic phase liquid crystalline material. The amounts were: lecithin 0.418 grams, oleyl alcohol 0.152 grams, glycerol 0.458 grams, and methyl paraben 0.052 grams. The result was a milky-white dispersion of microparticles coated with methyl paraben.

15 The protection of water-sensitive active compounds is important in, for example, oral health care products incorporating actives that are hydrolytically unstable.

#### EXAMPLE 12

In this example capsaicin was incorporated in particles coated with potassium nitrate, and where the nanostructured reverse bicontinuous cubic phase material is based on extremely 20 inexpensive surfactants. The coating is easily removed by simply adding water -- such as in a crop-spraying gun which merges a stream of the dispersion with a stream of water, as it aerosolizes the liquid into droplets. Note that the potassium nitrate would serve a dual purpose as a fertilizer.

25 The nonionic surfactants "OE2" (0.597 grams) and "OE5" (0.402 grams) were mixed with 0.624 grams of water which had been saturated with potassium nitrate. To this mixture the active compound capsaicin (in pure crystalline form, obtained from Snyder Seed Corporation) was added in the amount of 0.045 grams. Next, 0.552 grams of this mixture were removed, 0.135 grams of potassium nitrate were added, and the complete mixture heated to 80°C for 5 minutes. An upper solution was prepared by taking a 2% aqueous solution of PLURONIC F-68 30 and saturating it with potassium nitrate. The melted mixture was shaken to mix it, then put back

in the 80°C oven for 2 minutes. The test tube was then plunged in 20°C water for 5 minutes, at which point the upper solution was overlaid, and the entire mix stirred with a spatula, capped, shaken, and sonicated. The result was a dispersion of microparticles coated with potassium nitrate, and containing the active ingredient capsaicin in the interior.

5 When the dispersion was diluted with an equal volume of water, the coating was dissolved (in accordance with the high solubility of potassium nitrate in water at room temperature), and this was manifested as a rapid coagulation and fusion of the particles into large clumps. The interior of each particle was a tacky liquid crystal, so that in the absence of a coating, flocculation and fusion occur.

10 The example that we discuss here is that of a spray that would be used on decorative plants and/or agricultural crops, and would deter animals from eating the leaves. We have succeeded in encapsulating the compound capsaicin, which is a non-toxic compound (found in red peppers and paprika) that causes a burning sensation in the mouth at concentrations in the range of a few parts per million. Capsaicin has a record of commercial use as a deterrent to 15 rodents and other animals.

Pure capsaicin was encapsulated in the cubic phase interior of particles having a coating of crystalline potassium nitrate -- saltpeter. The exterior solution outside the particles was a saturated aqueous solution of potassium nitrate, which prevents dissolution of the coating until it is diluted; a dilution of the dispersion with water by approximately 1:1 resulted in nearly 20 complete dissolution of the particle coatings. (This dissolution was captured on videotape and, on viewing the tape, it was clear that there was dissolution of the coating and subsequent fusing of the particle interiors.)

Upon dilution and subsequent dissolution of the coating, the interior of the particle was exposed, this being a cubic phase with the following crucial properties:

25 A) it was insoluble in water;  
B) it was extremely tacky, adhesive; and  
C) it has very high viscosity.

Together these three properties imply that the de-coated cubic phase particles should adhere to plant leaves, and property A means that it will not dissolve even when rained on.

30 The same three properties were also crucial to the success of animal tests of the bulk cubic phase, used as a controlled-release paste, in the delivery of photodynamic therapy (PDT) pharmaceutical agents for the treatment of oral cancer.

The concentration of capsaicin achieved in the cubic phase particles was two orders of magnitude higher than in pharmaceutical preparations used in the treatment of arthritis. Higher loadings, perhaps as high as 20%, may be possible.

From the standpoint of commercializability, the components in the dispersion are 5 extremely inexpensive, and all are approved for use in foods, for topical application, and the like. In addition, potassium nitrate is a well-known fertilizer.

#### EXAMPLE 13

This example used capsaicin / potassium nitrate as in the previous example, but here the 10 nanostructured reverse bicontinuous cubic phase material is based on lecithin, which is an essential compound in plant and animal life, and can be obtained cheaply. This nanostructured reverse bicontinuous cubic phase material is also stable over a wide temperature range, at least to 40°C as might be encountered under normal weather conditions.

Soy lecithin (EPIKURON 200), in the amount of 1.150 grams, was mixed with 0.300 grams of oleyl alcohol, 1.236 grams of glycerol, and 0.407 grams of potassium nitrate. The 15 active capsaicin was added to this in the amount of 0.150 grams, and the mixture thoroughly mixed. Next, 0.50 grams of potassium nitrate were added, and the complete mixture heated to 120° C for 5 minutes. An upper solution was prepared by taking a 2% aqueous solution of PLURONIC F-68 and saturating it with potassium nitrate. The melted mixture was stirred, then put back in the 120° C oven for 3 minutes. The test tube was then plunged in cold water for 5 minutes, at which point the upper solution was overlaid, and the entire mix stirred with a spatula, capped, shaken, and sonicated, then alternated between shaking and sonicating for 30 cycles. The result was a dispersion of microparticles coated with potassium nitrate, and containing the active ingredient capsaicin in the interior at a level of approximately 5%. Also present were crystals of excess potassium nitrate.

25 The applications are similar to those of Example 12, except that the use of lecithin in the interior could provide for better integration of the particle interior with the plant cell membranes, possibly yielding better delivery.

#### EXAMPLE 14

In this example cupric ferrocyanide-coated particles were shown to be resistant to shear. 30 A nanostructured reverse bicontinuous cubic phase material was prepared by mixing

0.296 grams of sunflower monoglycerides (DIMODAN LS) with 0.263 grams of a 10% aqueous solution of potassium ferrocyanide. An upper solution was prepared by adding 0.021 grams of cupric sulfate and 0.063 grams of PLURONIC F-68 to 4.44 grams of water. The upper solution was overlaid onto the nanostructured reverse bicontinuous cubic phase material, the test tube sealed with a twist cap, and the system sonicated for 45 minutes. The result was a high concentration of microparticles, coated with cupric ferrocyanide, and with diameters on the order of 3 microns. This process produces microparticles without requiring temperature excursions, except those associated with sonicating, and these can be circumvented by using another form of emulsification. Furthermore, no excursions in pH were required.

When a droplet was placed between microscope slide and cover slip for microscopic examination, it was found that the cupric ferrocyanide-coated particles were fairly resistant to shear: when the cover slip was massaged over the dispersion, light pressure with the fingers did not induce any noticeable loss of shape or fusion of the particles. This was in contrast with, for example, particles coated with magnesium carbonate hydroxide, where light pressure induced a high degree of shape loss and fusing of particles. These observations were in accordance with the high stiffness of cupric ferrocyanide.

Particles with coatings resistant to shear could be important in applications requiring pumping of the particles, where traditional polymer-coated particles are known to suffer lifetime limitations due to degradation of the coating with shear.

20

#### EXAMPLE 15

In this example capsaicin was incorporated at a fairly high loading, namely 9 wt %, into the interiors of crystal-coated particles of the present invention. A nanostructured reversed bicontinuous cubic phase was produced by mixing 0.329 grams of lecithin, 0.109 grams oleyl alcohol, 0.611 grams glycerol, and 0.105 grams of capsaicin (obtained in crystalline form as a gift from Snyder Seed Corp., Buffalo, NY). To this cubic phase were added 0.046 grams of cupric sulfate. An upper solution was prepared by mixing 0.563 grams of 10% potassium ferrocyanide aqueous solution with 2.54 grams of water. The upper solution was overlaid onto the cubic phase-cupric sulfate mixture, and the tube sonicated for two hours. The reaction that forms cupric ferrocyanide was easily evidenced by the deep reddish-brown color of the compound. At the end of this time, the cubic phase was dispersed into cupric ferrocyanide-coated particles. The coating was made of cupric ferrocyanide, which is a strong material and has

some selective permeability to sulfate ions. Since this coating material is a robust crystal, as seen from Example 14, and capsaicin is extremely unpleasant to the taste of rodents, these particles could be useful as rodent deterrents in preventing damage to corrugated boxes, agricultural plants, etc., particularly where the particles must be resistant to mild shear (as during production of the particle-laced boxes, or deposition of the particles onto plants), prior to the gnawing action of rodents which would open the microparticles and expose the capsaicin to the animal's tastebuds.

#### EXAMPLE 16

In this example microparticles with a cupric ferrocyanide coating were produced using the same procedure as in Example 14, but in this case an antibody was incorporated as the active agent. In particular, anti 3', 5' cyclic adenosine monophosphate (AMP) antibody was incorporated as an active agent at a loading of 1 wt% of the interior. A cubic phase was prepared by mixing 0.501 grams of sunflower monoglycerides with 0.523 grams of water. Potassium ferrocyanide, in the amount of 0.048 grams, was added to the cubic phase, together with approximately 0.010 grams of the antibody. Excess aqueous solution was removed after centrifuging. An upper solution was prepared by adding 0.032 grams of cupric nitrate and 0.06 grams of PLURONIC F-68 to 3.0 grams of water. After overlaying the upper solution and sonicating, a milky-white dispersion of microparticles, coated with cupric ferrocyanide, was obtained. Such particles could be useful in a biotechnology setting such as a bioreactor, in which the stiff cupric ferrocyanide coating would be useful in limiting release during mild shear conditions encountered (for example, in a pressurized inlet), prior to the desired release of coating and availability of the bioreactive antibody.

#### EXAMPLE 17

In this example ethylhydrocupreine forms an extremely hard shell. In this example an acid-base process was used.

A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.648 grams of sunflower monoglycerides (DIMODAN LS) with 0.704 grams of water. To this were added 0.084 grams of ethylhydrocupreine hydrochloride, and a trace of methylene blue. An upper solution was prepared by adding 1.01 grams of 0.1M sodium hydroxide and 0.052 grams of PLURONIC F-68 to 3.0 grams of water. After overlaying the upper solution onto the liquid

crystal, the system was sonicated, resulting in a dispersion of microparticles coated with ethylhydrocupreine (free base). Most of the particles were less than a micron in size, when examined with optical microscopy.

5 Particles which maintain integrity with dessication could be useful in, for example, slow-release of agricultural actives (herbicides, pheromones, pesticides, etc.), where dry weather conditions could cause premature release of less resistant particles.

#### EXAMPLE 18

In this example leucine-coated particles were created by a heating-cooling protocol.

10 A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 1.51 grams of sunflower monoglycerides (DIMODAN LS) with 0.723 grams of water. To 0.52 grams of the nanostructured reverse bicontinuous cubic phase material taken from this mixture were added 0.048 grams of DL-leucine. The mixture was stirred well and heated to 80° C, then cooled to room temperature by plunging in water. Immediately a 2% solution of PLURONIC F-68 in water was overlaid, the mixture shaken, and then sonicated. This resulted in a milky 15 dispersion of microparticles coated with leucine.

20 The ability to make the same coating (in this case leucine) by either a thermal method or an acid-base method provides important flexibility in production, since, for example, certain actives (proteins, for example) are very easily denatured with temperature but can be quite resistant to pH, whereas other compounds can be resistant to temperature but can hydrolyze at acidic or basic pH.

#### EXAMPLE 19

This example shows that interior components can be protected from contact with oxygen, even when oxygen was bubbled into the exterior medium (here water.)

25 A nanostructured reverse bicontinuous cubic phase material (with excess water) was prepared by mixing 2.542 grams of sunflower monoglycerides with 2.667 grams of water. From this, 0.60 grams of nanostructured reverse bicontinuous cubic phase material were removed. Next, 0.037 grams of DL-leucine and 0.497 grams of 1M HCl were mixed and dried, after which 0.102 grams of water were added, to yield a solution of leucine hydrochloride, which was added to the 0.60 grams of nanostructured reverse bicontinuous cubic phase material, along with a trace 30 of methyl red dye. The nanostructured reverse bicontinuous cubic phase material was a strong

yellow color, but when spread out as a film it turned crimson-red in about 3 minutes. due to oxidation. An upper solution was prepared by mixing 0.511 grams of 1M sodium hydroxide, 0.013 grams of PLURONIC F-68, and 2.435 of water. A dispersion of leucine-coated, methyl red-containing microparticles was prepared by overlaying the upper solution onto the liquid crystal and sonicating. It was first checked that a solution of methyl red in water, with or without F-68 added, quickly changes from yellow to crimson-red when air was bubbled through. Then, when air was bubbled through the dispersion of methyl red-containing microparticles, it was found that the color did not change from yellow, thus demonstrating that the encapsulation of the methyl red inside the microparticles protected the methyl red against oxidation.

Particles such as these which are able to protect the active compound from contact with oxygen could be useful in protecting oxygen-sensitive compounds. such as iron dietary supplements for example. during long storage.

#### EXAMPLE 20

In this example the water substitute glycerol was used both in the interior nanostructured reverse bicontinuous cubic phase material, and as the exterior (continuous) coating, thus substantially excluding water from the dispersion.

A dispersion of microparticles was prepared using glycerol instead of water, by mixing soy lecithin and oleyl alcohol in the ratio 2.4:1, then adding excess glycerol and mixing and centrifuging. An amount of 0.70 grams of this nanostructured reverse bicontinuous cubic phase material was mixed with 0.081 grams of methyl paraben. An upper solution was prepared by adding cetylpyridinium bromide to glycerol at the level of 2%. The nanostructured reverse bicontinuous cubic phase material-methyl paraben mixture was sealed and heated to 120° C, mixed well, reheated to 120° C, and then plunged into cold water, at which point the upper solution was overlaid and the test tube re-sealed (with a twist-cap) and sonicated. This resulted in microparticles, coated with methyl paraben, in a glycerol continuous phase. Such a glycerol-based dispersion is of interest in the microencapsulation of water-sensitive actives.

Using microparticle dispersions such as these, hydrolytically unstable actives, which are encountered in a wide range of applications, can be protected against contact with water even after release of the coating.

Similar to Example 6 above, where zinc is used to challenge encapsulated methylene blue, but here the coating is potassium nitrate. In addition, the same dispersion is also subjected to challenge by potassium dichromate.

A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.667 grams of soy lecithin, 0.343 grams of oleyl alcohol, 0.738 grams of glycerol, and a trace of methylene blue. To 0.469 grams of the equilibrated phase was added 0.225 grams of potassium nitrate. An upper solution was prepared by adding 2% PLURONIC F-68 to a saturated aqueous solution of potassium nitrate. This was overlaid onto the liquid crystal, and the system sonicated until the liquid crystal was dispersed into microparticles, coated with potassium nitrate. The 10 color of the dispersion was light blue. Two tests were then used to show that the methylene blue was protected by encapsulation in the microparticles. To approximately 1 ml of this dispersion was added approximately 0.1 grams of finely powdered zinc: when powdered zinc contacts methylene blue in solution, it causes a loss of color. After shaking, the mixture was centrifuged very briefly, with about 10 seconds total time loading into the centrifuge, centrifuging, and 15 removing from the centrifuge; this was done to avoid interference from the zinc in determining the color of the methylene blue-containing particles. It was found that there was very little, if any, decrease in blue color from the treatment with zinc, showing that the microparticle coating protected the methylene blue from contact with the zinc. Then, potassium dichromate was added to another aliquot of the original light-blue dispersion. This changed the color to a greenish 20 color, with no hint of the purplish-brown that results if methylene blue in solution were contacted with potassium dichromate.

Coated particles of this Example feature an extremely cost-effective coating material, potassium nitrate, and yet protect active compounds against chemical degradation from outside conditions, making them of potential importance in, for example, agricultural slow-release.

25

#### EXAMPLE 22

This provides an example of microparticles with a permselective coating of a inclusion compound. This particular inclusion compound, a so-called Werner complex, has the property that the porosity remains when the guest molecule is removed. Clathrate and inclusion compound coatings are of interest as coatings of selective porosity, where selectivity for release or 30 absorption can be based on molecular size, shape, and/or polarity.

A nanostructured reverse bicontinuous cubic phase material was first prepared by mixing

0.525 grams of sunflower monoglycerides and 0.400 grams of water. To this were added 0.039 grams of manganese chloride ( $MnCl_2$ ) and 0.032 grams of sodium thiocyanate. An upper solution was prepared by adding 0.147 grams of 4-picoline (4-methylpyridine) to 3.0 ml of a 2% aqueous solution of PLURONIC F-68. The upper solution was overlaid on the liquid crystal mixture, and the test tube sealed and sonicated. The nanostructured reverse bicontinuous cubic phase material was thus dispersed into microparticles coated with the manganese form of the Werner complex, namely  $Mn(NCS)_2(4\text{-MePy})_4$ .

The coating in this example may find use in the removal of heavy metals from industrial streams. In this case the coating can be a porous crystal -- known as a clathrate -- which permits atomic ions to pass across the coating and into the cubic phase interior, which is an extremely high-capacity absorbent for ions due to the high surface charge density (using an anionic surfactant, or more selective chelating groups such as bipyridinium groups, etc.). Most likely permanent pores would be the best. The selectivity afforded by the clathrate coating circumvents the reduction in sorbent power that is inevitable with traditional sorbents (such as activated carbon and macroreticular polymers), due to larger compounds that compete with the target heavy metal ions for the available adsorption sites. Regeneration of the sorbent could be by ion-exchange, while keeping the particles and coatings intact (this latter step would, incidentally, be an example of release).

#### EXAMPLE 23

In this example coated particles with an outer coating comprising methyl paraben and having a special dye disposed in the nanostructured reverse bicontinuous cubic phase material were challenged with a cyanide compound, which would cause a color change in the event of contact with the dye. Since the cyanide ion is extremely small, the success of this test shows that the coating is impervious even to very small ions.

A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.424 grams of sunflower monoglycerides and 0.272 grams of water. To this were added 0.061 grams of methyl paraben and a trace of the dye 1,2-pyridylazo-2-naphthol. An upper solution of 1% cetylpyridinium bromide was prepared. The liquid crystal was heated in a 120° C oven for five minutes, stirred vigorously, reheated, then plunged into cold water, and which time the upper solution was overlaid, the test tube sealed, and put in a sonicator. The result was a dispersion of methyl paraben-coated microparticles, with average size on the order of 1 micron.

Cuprous cyanide was then used to demonstrate that the dye was protected from contact with the exterior phase. When cuprous cyanide was added to a solution of 1,2-pyridylazo-2-naphthol (whether in the presence of F-68, or not), the color changes from orange to strong purple. However, when cuprous cyanide was added to an aliquot of the dispersion of dye-containing particles, there was no color change, showing that the dye was protected from contact with the cuprous cyanide by the methyl paraben coating. One can calculate that the diffusion time of a cuprous ion into the center of a 1 micron particle is on the order of a few seconds or less, which would not have prevented the color change had the coating not sealed off the particle.

The protection of active compounds from contact with ions from the outside environment could be useful in, for example, drug delivery, in particular in delivery of a polyelectrolyte which could be complexed and inactivated by contact with multivalent ions.

#### EXAMPLE 24

In this example the cyanide ion test of the previous example was repeated for potassium nitrate-coated particles.

A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.434 grams of sunflower monoglycerides and 0.215 grams of water. To this were added 0.158 grams of potassium nitrate and a trace of the dye 1,2-pyridylazo-2-naphthol. An upper solution of 1% cetylpyridinium bromide in saturated aqueous potassium nitrate was prepared. The liquid crystal was heated in a 120° C oven for five minutes, stirred vigorously, reheated, then plunged into cold water, at which time the upper solution was overlaid, the test tube sealed, and put in a sonicator. The result was a dispersion of potassium nitrate-coated microparticles. When cuprous cyanide was added to an aliquot of the dispersion of dye-containing particles, there was only a slight change of color, showing that the dye was substantially protected from contact with the cuprous cyanide by the potassium nitrate coating.

The utility of these particles is similar to those in Example 23, but the cost-effective coating potassium nitrate was used in this Example.

#### EXAMPLE 25

A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.913 grams of soy lecithin (EPIKURON 200), 0.430 grams of oleyl alcohol, and 0.90 grams of glycerol (excess glycerol). After mixing thoroughly and centrifuging, 0.50 grams of the

nanostructured reverse bicontinuous cubic phase material were removed and 0.050 grams of dibasic sodium phosphate added. An upper solution was prepared by adding 0.10 grams of calcium chloride to 3 ml of an aqueous solution containing 2% PLURONIC F-68 and 1% cetylpyridinium bromide. After overlaying the upper solution on the liquid crystal - sodium phosphate mixture, the test tube was sealed and sonicated. The result was a dispersion of 5 microparticles coated with a calcium phosphate. Calcium phosphate coatings were of inherent interest in biological contexts since calcium phosphates were a major component of bone, teeth, and other structural components.

#### EXAMPLE 26

10 This example shows that the magnesium carbonate-coated particles in the example retain their integrity upon dessication, that is, when the exterior water phase was dried off. Thus, dry powders can be produced while retaining the interior as a water-rich liquid crystalline phase material.

15 "Tung-sorbitol compound" preparation. Initially, a "tung-sorbitol compound" was prepared as follows:

An amount of 110 grams of tung oil (obtained as Chinese Tung Oil from Alnor Oil) was combined in a reaction flask with 11.50 grams of sorbitol. The flask was purged with argon, sealed and heated to 170° C, and stirred magnetically. Sodium carbonate (3.6 grams) were added and the mixture stirred at 170° C for 1 hour. At this point, 3.4 grams of 3-chloro-1,2- 20 propanediol were added, and the mixture was cooled to room temperature. Seventy-five milliliters of the oily phase from this reaction were mixed with 300 ml of acetone, and a white precipitate removed after centrifugation. Next, 18 grams of water and 100 ml of acetone were added, the mixture centrifuged, and an oil residue on the bottom removed. Then 44 grams of water were added, and the bottom phase again collected and discarded. Finally, 20 grams of 25 water were added and this time the oily residue on the bottom collected and dried under argon flow. This yielded approximately 50 ml of a tung fatty acid ester of sorbitol, which was referred to hereinafter as "tung-sorbitol product".

Example 26A. A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.110 grams of the "tung-sorbitol product", 0.315 grams of soy lecithin, and 0.248 30 grams of water, mixing thoroughly, and centrifuging. To this was added 0.085 grams of potassium carbonate. An upper solution was then prepared by adding 0.118 grams of

PLURONIC F-68 and 0.147 grams of magnesium sulfate to 5.34 grams of water. The upper solution was overlaid onto the liquid crystal, and the test tube sealed, shaken, sonicated for 2 hours, and finally shaken well again. The result was a milky-white dispersion of microparticles coated with magnesium carbonate hydroxide. This was diluted, by adding two parts water to one part dispersion, in order to dissolve excess inorganic crystalline material. A small drop of the dispersion was spread gently onto the surface of a microscope slide, and allowed to dry. After ten minutes of drying, the water exterior to the particles was almost completely evaporated. Microscopic examination showed that the particles nevertheless retained their shape, and did not become amorphous blobs, as was observed if uncoated particles were dried in a similar manner (as the dried liquid crystalline mixture turns to a liquid).

Example 26B. The dispersion produced in Example 26A was heated to 40° C. According to phase behavior determinations, at this temperature the interior phase was a nanostructured liquid L2 phase material. The dispersion remained milky-white, and under the microscope showed the retention of microparticles as well. Since this L2 phase contains oil, water, and surfactant (namely the lecithin), it was also a nanostructured microemulsion.

#### EXAMPLE 27

In this example receptor proteins are disposed within the matrix of a nanostructured reverse bicontinuous cubic phase material in the internal core of magnesium carbonate-coated particles, then the coated particles were in turn embedded in a hydrogel. The coating on the particles can be used to protect the receptor protein during shipping and storage, and then easily removed by washing just before use. This example and Example 28 presage the use of coated particles of the present invention for, e.g., affinity chromatography, using hydrogel beads with coated particles of the present invention embedded in them.

An amount of 0.470 grams of soy lecithin (EPIKURON 200) was mixed with 0.183 grams of the "tung-sorbitol product", and 0.359 grams of water. To this was added 0.112 grams of potassium carbonate. This was centrifuged for several hours and the excess aqueous phase removed. A preparation of torpedo nicotinic acetylcholine receptor was prepared according to the protocol described by L. Pradier and M. G. McNamee in *Structure and Function of Membranes* (ed. P. Yeagle, 1992, pp. 1047-1106). In this preparation, 50 micrograms of receptor protein was contained in 50 microliters of lipid, most of which was dioleoylphosphatidylcholine (DOPC). (The remainder was other membrane lipid components, such as other phospholipids,

cholesterol, etc.) This amount of preparation was added to the nanostructured reverse bicontinuous cubic phase material-potassium carbonate mixture, and the entire mixture stirred gently but long enough to ensure good mixing, as checked by the absence of birefringence. An upper solution was prepared by adding 0.328 grams of magnesium sulfate, 0.324 grams of 5 PLURONIC F-68, and 0.0722 grams of cetylpyridinium bromide to 20.02 grams of water. Five grams of the upper solution were overlaid onto the test tube containing the receptor-loaded nanostructured reverse bicontinuous cubic phase material, and the test tube sealed, shaken, and sonicated for 2 hours. This resulted in a dispersion of magnesium carbonate hydroxide-coated, receptor-containing microparticles, a substantial fraction of which were in the size range of 0.5 to 10 1 micron.

The microparticles were then immobilized in a polyacrylamide hydrogel. Acrylamide (0.296 grams), methylene-bis-acrylamide (0.024 grams, as crosslinker), ammonium persulfate (0.005 grams, as initiator), and tetramethylethylene diamine (TMED, 0.019 grams, as co-initiator) were added to the dispersion, resulting in polymerization of the acrylamide into a 15 crosslinked hydrogel in less than 30 minutes. A thin slice of the hydrogel was examined under a microscope, and a high concentration of microparticles was seen, just as with the original dispersion.

The hydrogel was furthermore fragmented into bits with size approximately 30 microns. This was accomplished by pressing the hydrogel through a wire mesh with a 40 micron mesh 20 size.

#### EXAMPLE 28

In this example receptor proteins were disposed in the internal core of coated particles of the present invention where the coating was potassium nitrate, and the coated particles in turn immobilized in hydrogel beads. The receptor-laden beads were successfully tested for binding 25 activity in radioassays performed at UC Davis.

An amount of 0.470 grams of soy lecithin (EPIKURON 200) was mixed with 0.185 grams of the "tung-sorbitol product", and 0.368 grams of water. To this was added 0.198 grams of potassium nitrate, and the contents thoroughly mixed. A preparation of torpedo nicotinic acetylcholine receptor was prepared as described in the previous Example. In this preparation, 30 per every 50 micrograms of receptor protein was contained in 50 microliters of lipid, most of which was dioleoylphosphatidyl-choline (DOPC). Fifty-five milligrams of preparation was

added to the nanostructured reverse bicontinuous cubic phase material-potassium carbonate mixture, and the entire mixture stirred gently but long enough to ensure good mixing. An upper solution was prepared by adding 0.128 grams of PLURONIC F-68 and 0.015 grams of cetylpyridinium bromide to 6.05 grams of saturated aqueous potassium nitrate solution. The 5 nanostructured reverse bicontinuous cubic phase material-potassium nitrate preparation was heated to 40° C to dissolve potassium nitrate, then plunged into 10° C water for 10 minutes. The upper solution was overlaid onto the test tube containing the receptor-loaded nanostructured reverse bicontinuous cubic phase material, and the test tube sealed, shaken, and sonicated for 2 hours. This resulted in a dispersion of potassium nitrate-coated, receptor-containing 10 microparticles, a substantial fraction of which were in the size range of 0.3 to 1 micron.

The microparticles were then immobilized in a polyacrylamide hydrogel. Acrylamide (0.365 grams), methylene-bis-acrylamide (0.049 grams, as crosslinker), ammonium persulfate (0.072 grams of a 2% solution, as initiator), and tetramethylethylene diamine (TMED, 0.011 grams, as co-initiator) were added to the dispersion, resulting in polymerization of the 15 acrylamide into a crosslinked hydrogel in a matter of hours. A thin slice of the hydrogel was examined under a microscope, and a high concentration of microparticles was seen (except near the very bottom of the hydrogel), just as with the original dispersion.

The hydrogel was furthermore fragmented into bits with size approximately 30 microns. This was accomplished by pressing the hydrogel through a wire mesh with a 40 micron mesh 20 size. At a 40 micron bit size, one can estimate that the diffusion time for a small molecule into the center of a bit is on the order of a second or less, which does not have a significant impact on the receptor tests reported next.

Using <sup>125</sup>I-labeled bungarotoxin as the ligand, an assay of receptor binding was performed 25 using the nanostructured reverse bicontinuous cubic phase material microparticle-immobilized acetylcholine receptor system just described. (The standard assay for binding has been described in publications from Dr. Mark McNamee's group.) The results showed that the nanostructured reverse bicontinuous cubic phase material microparticle-immobilized acetylcholine receptor system exhibited binding of the bungarotoxin at approximately 70% of the level measured with the standard receptor preparation, demonstrating the retention of protein binding properties 30 throughout not only the immobilization procedure, but also the period (more than two months) that elapsed between the date on which the sample was prepared and the date it was tested.

The foregoing Examples 26-28 actually show the application of the particles in

biochemical assays, and show a large improvement in stability over the commonly used liposomes, which are inconvenient due to their inherent instabilities. Such assays are important in clinical diagnoses, as well as in pharmaceutical drug screening.

#### EXAMPLE 29

5 As in Example 22 above, clathrate-coated particles were produced in this example. In this example the nanostructured reverse bicontinuous cubic phase material interior can be polymerized, by the effect of oxygen which can pass through the coating (the coating nevertheless prevents passage of water).

10 Lecithin extracted from Krill shrimp was obtained as Krill shrimp phosphatidylcholine from Avanti Polar Lipids of Birmingham, Alabama. An amount of 0.220 grams of this lecithin was mixed with 0.110 grams of "tung-sorbitol product". 0.220 grams of water. 0.005 grams of a cobalt dryer (from the art materials supply company Grumbacher) containing cobalt naphthenate, and 0.30 grams of potassium thiocyanate. This formed a green-colored nanostructured reverse bicontinuous cubic phase material. An upper solution was prepared by adding 0.309 grams of 15 manganese chloride, 0.105 grams of 4-picoline (4-methyl pyridine), 0.113 grams of PLURONIC F-68, and 0.021 grams of cetylpyridinium bromide to 5.10 grams of water. The upper solution was overlaid on the nanostructured reverse bicontinuous cubic phase material, the test tube sealed, shaken, and sonicated, with ice water filling the sonication bath water. As the green-color nanostructured reverse bicontinuous cubic phase material was dispersed into 20 microparticles, the reaction caused a color change to brown. After two hours, substantially all of the nanostructured reverse bicontinuous cubic phase material had been dispersed into particles, which were mostly submicron in size. The coating was a Werner compound, which according to the literature has channels that allow the absorption of (or passage of) molecular oxygen. The high degree of unsaturation in the Krill lecithin, as well as that in the tung-sorbitol product, 25 together with the catalytic action of the cobalt dryer, makes it possible to polymerize this microencapsulated nanostructured reverse bicontinuous cubic phase material by contact with atmospheric oxygen.

The clathrates described in this example were discussed above (Example 22.)

#### EXAMPLE 30

30 In this example a nanostructured reversed hexagonal phase material was dispersed.

A nanostructured reversed hexagonal phase material was prepared by mixing 0.369 grams of soy lecithin (EPIKURON 200). 0.110 grams of sorbitan trioleate, and 0.370 grams of glycerol. To this nanostructured reversed hexagonal phase material was added 0.054 grams of magnesium sulfate. An upper solution was prepared by adding 0.10 grams of potassium carbonate, 0.10 grams of PLURONIC F-68, and 0.02 grams of cetylpyridinium bromide to 5 grams of water. The upper solution was overlaid on the nanostructured reversed hexagonal phase material, and the test tube sealed, shaken and sonicated for one hour, resulting in a dispersion of most of the nanostructured reversed hexagonal phase material into microparticles coated with magnesium carbonate hydroxide.

10 The dimensionality of the pores (cylindrical) in the reversed hexagonal phase provides a unique release kinetics profile which could be useful in, for example, controlled drug delivery.

#### EXAMPLE 31

In contrast with most of the above examples, the nanostructured reversed hexagonal phase material that was dispersed in this example was not in equilibrium with excess water, although it was insoluble in water.

15 Soy lecithin (0.412 grams), linseed oil (0.159 grams), and glycerol (0.458 grams) were thoroughly mixed, producing a nanostructured reversed hexagonal phase material at room temperature. To this nanostructured reversed hexagonal phase material was added 0.059 grams of magnesium sulfate. An upper solution was prepared by adding 0.10 grams of potassium carbonate, 0.10 grams of PLURONIC F-68, and 0.02 grams of cetylpyridinium bromide to 5 grams of water. The upper solution was overlaid on the nanostructured reversed hexagonal phase material, and the test tube sealed, shaken and sonicated for 30 minutes, resulting in a dispersion of most of the nanostructured reversed hexagonal phase material into microparticles coated with magnesium carbonate hydroxide.

20 The ability to disperse nanostructured phases which are not in equilibrium with excess water expands the range of chemistries which can be used in the present invention. This versatility is especially important in demanding applications, such as drug delivery, where a large number of product criteria must be simultaneously satisfied.

#### EXAMPLE 32

25 In this example, the nanostructured lamellar phase material was dispersed using a

chemical reaction process.

A nanostructured lamellar phase material was prepared by mixing 0.832 grams of soy lecithin (EPIKURON 200) and 0.666 grams of water. To approximately 0.80 grams of this nanostructured lamellar phase material was added 0.057 grams of magnesium sulfate. An upper 5 solution was prepared by adding 0.10 grams of potassium carbonate, 0.10 grams of PLURONIC F-68, and 0.02 grams of cetylpyridinium bromide to 5 grams of water. The upper solution was overlaid on the nanostructured reversed hexagonal phase material, and the test tube sealed, shaken and sonicated for five minutes, resulting in a dispersion of most of the nanostructured lamellar phase material into microparticles coated with magnesium carbonate hydroxide.

10 The particles in this Example bear a structural relationship with polymer-encapsulated liposomes, but do not suffer from the harsh chemical conditions used to produce polymer-encapsulated liposomes: the ability to produce, in a single step, lamellar phase-interior particles coated with a wide range of crystalline coatings, and under mild conditions, could make the present invention of importance in controlled release drug delivery.

15

### EXAMPLE 33

**Preparation of free bases.** Both ethylhydrocupreine and neutral red were purchased in the protonated hydrochloride form. In each case this salt was dissolved in water, to which was added aqueous sodium hydroxide in 1:1 molar ratio. The mixture of the two aqueous solutions produced a precipitate that was washed with water (to remove NaCl and any unreacted NaOH), 20 centrifuged and then dried above the melting point of the free base.

**Preparation of nanostructured reverse bicontinuous cubic phase dispersions.**

Formulation of dispersions began with the following mixture:

0.417 gm glycerol monooleate (GMO)

0.191 gm glycerol

25

0.044 gm ethylhydrocupreine (or, as the case may be, neutral red, both in free base form). Instead of the usual monoglyceride - water nanostructured reverse bicontinuous cubic phase material, the monoglyceride - glycerol nanostructured reverse bicontinuous cubic phase material was used in these examples.

An upper solution was made by dissolving PLURONIC F-68 in water to a level of 2%.

30

After weighing the components into a test tube and mixing with a spatula, the sealed (twist-cap) test tube was put in a 140° C oven for at least 20 minutes, and the ethylhydrocupreine

(or neutral red free base) was checked to have melted. The test tube was then plunged into water, which was below room temperature (about 10° C) in some cases and room temperature water in others; no difference was found in the dispersions in the two cases.

After the sample had been in the cooling water for about 5 minutes, the viscosity was  
5 checked to be very high, indicating a nanostructured reverse bicontinuous cubic phase; in some cases the sample was observed through crossed polars for optical isotropy (the crystalline coating domains are much smaller than the wavelength of light, too small to affect the optical properties). The PLURONIC upper solution was poured into the test tube until about half full. The tube was then shaken, by hand and with the use of a mechanical mixer. The solution became increasingly  
10 opaque as the bulk nanostructured reverse bicontinuous cubic phase material disappeared and went into dispersion.

15 **SEM characterization.** Scanning electron microscope (SEM) preparation did not involve any fixation technique whatsoever. A drop of dispersion was simply placed on a glass slide, the water evaporated, and a thin (2 nm) coating of carbon sputtered on to avoid charging effects. In the sputtering apparatus, before sputtering began the sample was deliberately held for about 5 minutes at a vacuum of  $5 \times 10^{-4}$  Torr. This was done to test the robustness of the particle coating. The SEM used was a Hitachi S-800 field-emission SEM, and was operated at 25 kV.

20 Figure 3 shows an SEM micrograph of an ethylhydrocupreine dispersion, and particles in the range of about 0.5-2 micron diameter are seen (the bottom half is a 10x magnification of the area boxed in the top half, so that the magnification is 500 on top and 5.000 on the bottom). Many of the particles, remarkably, distinctly show a polyhedral shape.

25 The measured particle size distribution for this sample (see the next section) showed that particles on the order of 0.5 - 2 microns diameter dominate in this dispersion, and this agrees well with the particles seen in the micrograph. One can estimate that the thickness of the ethylhydrocupreine coating in a 0.5 micron particle was about 10 nm, and this was clearly thick enough that it was able to protect the liquid components in the interior of the particles from evaporation in the 0.5 mTorr vacuum.

30 In this dispersion, the nanostructured reverse bicontinuous cubic phase material was loaded with lithium sulphate as a marker before dispersing, and indeed the EDX spectra of particles in this dispersion showed a sulfur peak. Lithium cannot be detected by the EDX used, and other peaks in the spectrum were attributed to the glass substrate.

Figure 4 shows an SEM micrograph of a neutral red dispersion. Substantially all of the

particles have sizes in the range of 0.3 - 1 micron.

**Particle size distribution.** A Malvern 3600E laser diffraction particle sizer was used to measure the distribution. For each dispersion checked, a few drops were added to the carrier fluid (water), resulting in a large dilution of the concentration so as to avoid multiple scattering.

5 The particle size was computed as the diameter of a sphere of the same volume, which is a good measure considering the polyhedral shape of the particles. (See below.) The instrument is capable of measuring particles down to at least 0.5 micron, and data on the distribution include contributions at least down to 0.5 microns.

10 The particle size distribution of a dispersion prepared with a 13:1 ratio of GMO:ethylhydrocupreine is shown in Figure 5. In general, as the ratio of nanostructured reverse bicontinuous cubic phase material to crystalline coating agent increases so does the particle size. The data for this dispersion show that, on a volume average basis, 10% of the particles have particle size less than 0.6 microns, this being represented by the equation  $D(v,0.1)=0.6$  micron. The narrowness of the distribution is indicated in two ways. First, the  $D(v,0.9)$  and  $D(v,0.1)$  are 15 each a factor of 2 from the (volume-weighted) average of  $D(v,0.5)=1.2$  micron. And second, the "span", which gives the width of the distribution as:

$$\text{span} = [D(v,0.9) - D(v,0.1)]/D(v,0.5)$$

is computed to be 1.4. These results indicate a fairly low degree of agglomeration.

20 A narrower distribution was indicated for a dispersion with GMO:neutral red = 10:1. The span is given as 1.1, and the (differential) particle size distribution was easily seen to be quite sharp, dropping off quickly above 2 micron.

25 A small particle size was measured for a dispersion prepared with a lower GMO:ethylhydrocupreine ratio, with a distribution averaging 0.8 microns, and a span of 1.2. Thus, particle size can be controlled by the ratio of nanostructured reverse bicontinuous cubic phase material to crystalline coating agent, with the particle size decreasing with decreasing ratio.

30 **Small-angle X-ray scattering (SAXS).** This was used to verify that the interior of the particles in an ethylhydrocupreine dispersion was a nanostructured reverse bicontinuous cubic phase material. The dispersion itself—not a concentrate of the particles—was loaded into a 1.5 mm x-ray capillary, which was transported to the laboratory of Dr. Stephen Hui at Roswell Park Cancer Center Biophysics Department. The SAXS camera was equipped with a rotating anode, and measurements were performed at 100kV, 40 mV power (4 kW). Data were collected using a

linear position-sensitive detector connected through an electronics setup to a Nucleus multichannel analyzer. The MCA has the capacity for 8,192 channels, but only 2,048 resolution was used to increase the counts per channel. Counting times on the order of an hour were used because the volume fraction of nanostructured reverse bicontinuous cubic phase material in the dispersion (which was about 85% of the particle volume) was on the order of 10%. The software package "PCA" was used for analysis of the data.

Figure 6 shows the measured SAXS intensity versus wave vector  $q$  plot. The wave vector  $q$  is related to the diffraction angle  $\theta$  and the wavelength  $\lambda$  of x-rays by the formula:

$$q = 4\pi (\sin \theta)/\lambda.$$

10 A d-spacing is calculated from the  $q$ -value of a Bragg reflection by:

$$d = 2\pi/q.$$

In Figure 6, vertical lines give the exact, calculated Bragg peak positions for a lattice with space group  $Pn\bar{3}m$  and lattice parameter 7.47 nm. This space group is well-established for nanostructured reverse cubic phases in the monoolein-water system, particularly for those which 15 are in equilibrium with excess water. (Indeed, in nanostructured reverse cubic phases which are in equilibrium with excess water, the space group  $Pn\bar{3}m$  almost exclusively appears). Lattice parameters for the monoolein-water nanostructured reverse cubic phase with space group  $Pn\bar{3}m$  are also close to 8 nm; a more exact comparison was impossible because of the substitution of glycerol for water in the present case. In any case, the lattice type and size deduced from this 20 SAXS scan are in exact accord with literature data for monoglyceride nanostructured reverse cubic phases.

In the space group  $Pn\bar{3}m$ , the Miller indices ( $hkl$ ) for the allowed peak positions, and the value of  $h^2+k^2+l^2$ , are: (110), 2; (111), 3; (200), 4; (211), 6; (220), 8; (221), 9; (222), 12; and higher. Looking at the data and the expected peak positions, it is clear that the peaks at the (110) 25 and (222) positions are strongly supported by the data. The (111) peak appears as a shoulder to the (110) peak on the right side of the scan, and as a small but discernible peak on the left side. The (200) peak is supported at least on the right side of the scan; this peak is always measured to be much less intense than the (110) and (111) peaks in monoglyceride  $Pn\bar{3}m$  phases, and in  $Pn\bar{3}m$  phases in general, and this has been found to be in accord with theoretical amplitude 30 calculations [Strom, P. and Anderson, D.M. (1992) Langmuir, 8:691]. The (211) peak is supported by data on the left side of the scan, and the (221) by data on the right side. The absence or low intensity of peaks between the (211) and (222) is a consequence of the low

concentration (10%) of nanostructured reverse bicontinuous cubic phase in the dispersion. since the intensity of diffracted x-rays varies as the square of the volume concentration. Despite this, the definitive peaks at the (110) and (222) positions, and the perfect agreement of the deduced lattice and lattice parameter with related systems in the literature provide strong support for the 5 conclusion that the SAXS data demonstrate nanostructured reverse bicontinuous cubic phase ordering in the particle interiors.

These particles could be useful in, for example, controlled release of antiseptics in oral rinses, where the solubilities of the two coatings at slightly lowered pH (on the order of 5) was in the right range to make delivery preferential at sites of bacterial activity.

10

#### EXAMPLE 34

High-pressure liquid chromatography (HPLC) was used to characterize the integrity under shear and pressure of two dispersions. one chosen to have a rigid coating -- cupric ferocyanide -- and the other a soft, easily disrupted coating, the latter to act essentially as a control, to quantify any release under pressure of the more rigid coating. In other words, if the 15 concentration of marker in the two dispersions were approximately the same, and the release of marker in the rigid system were a small fraction, say  $x\%$  (where  $x$  is substantially less than 100), of the release of marker in the soft system, then one could conclude that only  $x\%$  of the particles in the rigid system broke up under the pressure, and the remaining  $(100 - x)\%$  remained intact during the HPLC. (Indeed. this percentage  $100 - x$  is a lower limit: the actual percentage of 20 intact rigid particles would be calculated to be higher if it were found that some fraction of the soft particles in the control had actually remained intact. though this possibility is remote. In any case, the calculations were assumed to be on a worst case scenario, by assuming that all the control particles broke up.)

25

##### Preparation of the dispersions.

25

Example 34A. A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.499 grams of soy lecithin, 0.163 grams of oleyl alcohol, 0.900 grams of glycerol, and 0.124 grams of capsaicin. To 0.842 grams of the nanostructured reverse bicontinuous cubic phase material from this system was added 0.043 grams of sodium cholate. An upper solution was prepared by adding 1 drop of 1M HCl to 3.00 grams of pH 5 phosphate buffer. The upper 30 solution was overlaid onto the liquid crystalline material, and the test tube sealed and sonicated, resulting in a milky-white dispersion of microparticles.

Example 34B. A nanostructured reverse bicontinuous cubic phase material was prepared by mixing 0.329 grams of soy lecithin, 0.108 grams of oleyl alcohol, 0.611 grams of glycerol, and 0.105 grams of capsaicin. To this were added 0.046 grams of cupric sulfate. An upper solution was prepared by adding 0.563 grams of 10% potassium ferrocyanide solution to 2.54 5 grams of water. The upper solution was overlaid onto the liquid crystal, and the test tube sealed and sonicated, resulting in a milky-white dispersion of microparticles, coated with cupric ferrocyanide.

The concentration of marker, namely capsaicin, was comparable in the two samples. The final concentration in the cupric ferrocyanide dispersion was 2.44%, compared to 3.19% for 10 Example 34B -- a 30% difference, which will be accounted for in the calculations below.

Purified capsaicin was then run in HPLC, and found to have an elution time of 22 minutes (data not shown). Under these identical conditions, the two dispersions prepared above were run. The data for the particles of Example 34B is shown in Figure 7, and for the cupric ferrocyanide particles in Figure 8. Tables 1 and 2 give the integrated peaks corresponding to 15 Figures 7 and 8, respectively, as output from the HPLC computer: sampling rate was 5 Hz.

Clearly there is a strong peak in Figure 7 at 22 minutes elution time (numbered peak 13 by the computer), and Table 1 gives the integrated intensity of this peak as 3,939,401. A much smaller peak is seen at 22 minutes in Figure 8 (numbered 10 by the computer), and Table 2 gives the intensity as 304,929.

20 If these integrated peak values are normalized according to the concentration of capsaicin in the two samples, namely 3,939,401/0.0319 for the Example 34B case and 304,929/0.0244 for the cupric ferrocyanide case, the ratio of the normalized peak intensity for the cupric ferrocyanide case to the Example 34B case is 0.101 -- that is, at most 10.1% of the cupric ferrocyanide particles released the capsaicin marker under the HPLC conditions.

25 These particles have a coating which is a mineral of low aqueous solubility, making them of potential utility in applications requiring release of the particle coating by strong shear, while at the same time protecting against release due to simple dilution with water. An example of such an application would be where a rodent deterrent such as capsaicin, or rodent toxin, would be encapsulated, the particles impregnated into electrical wires, corrugated boxes, and 30 other products requiring protection against gnawing by rodents, and the gnawing action of a rodent would induce release of the active deterrent or toxin. The low water solubility would prevent the deterrent from premature release due to damp conditions.

TABLE 1: Integrated peak intensities, corresponding to Figure 7, for HPLC analysis of Example 34B particles containing capsaicin. Peak #13 is the main capsaicin peak.

Peak	Area
1	2914
5	2 8096
	3 2848
	4 29466
	5 11304
	6 2254
10	7 12871
	8 4955
	9 124833
	10 113828
	11 19334
15	12 7302
	13 3939401
	14 39153
	15 255278
	16 755868
20	17 52623
	18 19395
	19 4899
	20 10519
	21 5102
25	22 1481
	23 344230
	24 9971
	25 194442
	26 89831
30	27 80603
	28 105163
	29 186224

30	194020
31	36805
32	2115
33	23296
5	34 4327
	35 5166
	36 90236
	37 62606
	38 44523
10	39 110347
	40 4391
	41 1275597
	42 1353000
	43 238187

TABLE 2: Integrated peak intensities, corresponding to Figure 8, for HPLC analysis of cupric ferrocyanide-coated particles containing capsaicin. Peak #10 is the main capsaicin peak.

Peak	Area
1	1681172
5	2 3011240
	3 106006
4	2760
5	59059
6	38727
10	7 163539
	8 44134
9	6757
10	304929
11	10466
15	12 141800
	13 332742
14	14442
15	6996
16	15008
20	17 11940
	19 91446
20	250214
21	251902
22	203000
25	23 44658
	24 110901
25	24296
26	19633
27	25527
30	28 15593
	29 75442
30	30 40245

90

31 421437

EXAMPLE 35

A nanostructured cubic phase liquid crystal was prepared by mixing 0.77 grams of soy lecithin (EPIKURON 200, from Lucas-Meyer), 0.285 grams of oleyl alcohol, and 0.84 grams of glycerol, to which was added 0.11 grams of auric chloride. No heating was used in the 5 equilibration of this mixture, only mechanical stirring with a spatula. An amount 0.595 grams of this mixture was removed and smeared along the bottom half of the inner surface of a test tube. An upper solution was prepared by dissolving 0.14 grams of ferrous chloride and 0.04 grams of PLURONIC F-68 in 1.74 grams of distilled water. After overlaying the upper solution the test tube containing the cubic phase was sonicated, resulting in a dispersion of microparticles coated 10 with a gold coating. A control sample, in which the upper solution contained the F-68 but no ferrous chloride, was sonicated side by side with the first sample and did not result in a dispersion of microparticles. The reaction between ferrous chloride and auric chloride results in the precipitation of elemental, nonlamellar crystalline gold, which in the case of the first sample resulted in the creation of microparticles covered with gold, with cubic phase interior.

15 A glycerol - water mixture with a density approximately 1.2 gram/cc was then prepared by mixing 0.62 grams of glycerol with 0.205 grams of water, and approximately 0.1 grams of the dispersion was added to this, and the new dispersion centrifuged. A substantial fraction of the microparticles could be centrifuged to the bottom of this test tube after centrifuging for 3 hours, demonstrating that the density of these particles was significantly higher than 1.2; this was due to 20 the presence of the gold coating, since the density of the cubic phase was less than 1.2 -- indeed, a portion of the cubic phase which was not dispersed during the time of sonication could be centrifuged out of the original dispersions as a lower-density band, showing that this liquid was even less dense than the original dispersion.

Because gold is well-known for exhibiting chemical inertness, as well as good 25 mechanical properties when in the form of very thin films, and since it is also approved by the FDA for many routes of administration, gold-coated particles could be useful in safe, environmentally-friendly products demanding chemically and physically stable coatings. Furthermore, such particles could be effective in the treatment of arthritis, by providing greatly increased surface area of gold over other colloidal forms.

EXAMPLE 36

A nanostructured liquid phase containing the antineoplastic drug Paclitaxel was prepared

by solubilizing 0.045 grams of Paclitaxel, 0.57 grams of eugenol, 0.615 grams of soy lecithin (EPIKURON 200), 0.33 grams of glycerol, and 0.06 grams of cupric nitrate with 0.61 grams of methanol, and then evaporating off the methanol in an evaporating dish, with stirring during evaporation. An glycerol-rich upper solution was prepared by dissolving 0.09 grams of 5 potassium iodide, 0.05 grams of PLURONIC F-68, 0.44 grams of water and 1.96 grams of glycerol. After overlaying the upper phase, the system was sonicated, resulting in the dispersing of Paclitaxel-containing, nanostructured liquid phase into microparticles coated with crystalline iodine. Since these ingredients were chosen for their general acceptance as safe, inactive (except for the Paclitaxel itself) excipients in pharmaceutical preparations, this formulation or a variation 10 thereof could be of importance in the delivery of Paclitaxel for the treatment of cancer. The loading of Paclitaxel in the particle interior was quite high, namely on the order of 3 wt%, which in this case was so high that precipitation of some of the Paclitaxel within the interior of each particle may occur since the solubilization of Paclitaxel in this cubic phase at this high loading 15 was metastable. However, studies indicate that the precipitation is very slow, taking hours or even days, at such loadings, so that substantially all of the Paclitaxel remains in solution during the course of the production of particles; thereafter, the confinement of the Paclitaxel within the coated particles prevents the formation of large crystals (larger than a micron). If the concentration of paclitaxel in this system were lowered, to 0.7% or less of the interior, then the 20 solubilization of Paclitaxel becomes a truly stable solubilization (thermodynamic equilibrium), so that precipitation is prevented altogether. and microparticles of the present invention coated with nonlamellar crystalline iodine can be produced as described in this Example. Thus this system provides several scenarios for use in Paclitaxel delivery for cancer treatment.

#### EXAMPLE 37

A Paclitaxel-containing cubic phase liquid crystal was prepared by mixing 0.345 grams 25 of soy lecithin (EPIKURON 200), 0.357 grams of anisole, 0.26 grams of water and 0.02 grams of Paclitaxel (from LKT Laboratories); equilibration was speeded by plunging a test tube of the mixture, after vigorous stirring, into boiling water for one minute, then cooling to room temperature. To provide a coating material, 0.07 grams of propyl gallate was stirred in and the test tube again heated in boiling water. It had previously been checked that propyl gallate does 30 not dissolve appreciably in this cubic phase at room temperature, but that the solubility increases substantially at 100° C. An upper solution consisted of 2.25 grams of a 2% PLURONIC F-68

solution. The cubic phase - propyl gallate mixture was heated to 100° C, cooled to about 80° C, stirred with a spatula at the elevated temperature, and reheated to 100° C. After cooling the mixture for about 30 seconds, the upper solution was then overlaid on this mixture, and the test tube placed in a sonication bath for one hour. A dispersion of microparticles with Paclitaxel-containing interior and coated with propyl gallate was obtained. The dispersion had a high concentration of extremely fine microparticles (estimated particle diameter less than 0.4 microns), which were observable in the optical microscope at 1,000x by virtue of their Brownian motion. The overall particle size distribution was fairly broad, with some particles as large as 1-2 microns. Only a very small amount of precipitated Paclitaxel, in the form of needles, was observed, so that nearly all of it must be in the interiors of the microparticles. The concentration of Paclitaxel in this example was high enough that the solubilization was metastable, which has implication as discussed in the previous example. Since the concentration of the antineoplastic drug Paclitaxel in the interiors of these particles was about 2%, and the components of the formulation are on the FDA list of approved inactive excipients for oral delivery (and nearly all of them for injection as well), this formulation could be very important as a drug-delivery formulation for the treatment of cancers.

#### EXAMPLE 38

The amphiphilic polyethyleneoxide-polypropyleneoxide block copolymer PLURONIC F-68 (also called POLOXAMER 188), in the amount of 1.655 grams, was mixed with 0.705 grams of eugenol and 2.06 grams of water. Upon centrifugation, two phases resulted, the bottom phase being a nanostructured liquid phase, and the top a nanostructured cubic phase. An amount of 0.68 grams of the liquid crystalline phase was removed, and to it were added 0.05 grams of sodium iodide. A drop of eugenol was added to 2.48 grams of the lower phase to ensure low viscosity, and this nanostructured liquid phase, with 0.14 grams of silver nitrate added, served as the "upper solution" in dispersing the liquid crystalline phase. Thus, the liquid phase was overlaid on the liquid crystalline phase containing the iodide, and the mixture sonicated for 1.5 hours. The result was a dispersion of silver iodide-coated particles, in an external medium of the nanostructured liquid phase.

This Example illustrates the use of nanostructured liquid crystalline phases based on block copolymers as interior matrices for particles of the present invention. In this case, water

was used as a preferential solvent for the polyethyleneoxide blocks of the block copolymer, and eugenol as preferential solvent for the polypropyleneoxide blocks of the block copolymer (which are insoluble in water).

This Example also illustrates the use of a general approach discussed above, namely the use of a nanostructured phase as the mixture that serves as the "upper solution", providing moiety B which reacts with moiety A in the interior phase to cause precipitation of a crystalline coating material. In this case, B is the silver nitrate, which induces precipitation of silver iodide on contact with the interior matrix A (the cubic phase) which contains sodium iodide. As discussed above, it is generally desirable to choose this upper solution so that it is in equilibrium with the interior matrix, or, as in this case, very nearly so (the only deviation from true equilibrium being due to the addition of a single drop, about 0.01 grams or less than 0.5% of eugenol to the upper solution). As in this approach, it is generally useful to choose the interior matrix so that it is a viscous material, much more so than the upper solution which should be of relatively low viscosity.

It is apparent that many modifications and variations of the invention may be made without departing from the spirit and scope of the present invention. It is understood that the invention is not confined to the particular construction and arrangement herein described, but embraces such modified forms of it as come within the appended claims. The specific embodiments described are given by way of example only and the invention is limited only by the terms of the appended claims.

## CLAIMS

What is claimed is:

- 1 1. A coated particle comprising
  - 2 a. An interior core comprising a matrix consisting essentially of
    - 3 i. at least one nanostructured liquid phase,
    - 4 ii. at least one nanostructured liquid crystalline phase or
    - 5 iii. a combination of
      - 6 (1) at least one nanostructured liquid phase and
      - 7 (2) at least one nanostructured liquid crystalline phase and
  - 8 b. An exterior coating comprising a nonlamellar crystalline material.
- 1 2. A coated particle as defined by claim 1, wherein said nanostructured liquid phase material comprises
  - 2 a. a nanostructured L1 phase material,
  - 3 b. a nanostructured L2 phase material,
  - 4 c. a microemulsion that is nanostructured or
  - 5 d. a nanostructured L3 phase material.
- 1 3. A coated particle as defined by claim 1, wherein said nanostructured liquid crystalline phase material comprises
  - 2 a. a nanostructured normal or reversed cubic phase material,
  - 3 b. a nanostructured normal or reversed hexagonal phase material
  - 4 c. a nanostructured normal or reversed intermediate phase material or
  - 5 d. a nanostructured lamellar phase material.
- 1 4. A coated particle as defined by claim 1, wherein said nanostructured liquid phase material comprises
  - 2 a. a polar solvent and
  - 3 b. a surfactant or a lipid.
- 1 5. A coated particle as defined by claim 1, wherein said nanostructured liquid phase

- 1 material comprises
  - 2 a. a polar solvent,
  - 3 b. a surfactant or a lipid and
  - 4 c. an amphiphile or hydrophobe.
  
- 1 6. A coated particle as defined by claim 1, wherein said nanostructured liquid phase  
2 material comprises  
3 a. a block copolymer.
  
- 1 7. A coated particle as defined by claim 1, wherein said nanostructured liquid phase  
2 material comprises  
3 a. a block copolymer and  
4 b. a solvent.
  
- 1 8. A coated particle as defined by claim 1, wherein said nanostructured liquid crystalline  
2 phase material comprises  
3 a. a polar solvent and  
4 b. a surfactant.
  
- 1 9. A coated particle as defined by claim 1, wherein said nanostructured liquid crystalline  
2 phase material comprises  
3 a. a polar solvent,  
4 b. a surfactant and  
5 c. an amphiphile or hydrophobe.
  
- 1 10. A coated particle as defined by claim 1, wherein said nanostructured liquid crystalline  
2 phase material comprises  
3 a. a block copolymer.
  
- 1 11. A coated particle as defined by claim 1, wherein said nanostructured liquid crystalline  
2 phase material comprises  
3 a. a block copolymer and

1           b.       a solvent.

1 12.      A coated particle as defined by claim 1, wherein said interior core comprises an active  
2           agent disposed within said matrix.

1 13.      A coated particle as defined by claim 10, wherein said active agent comprises paclitaxel.

1 14.      A coated particle as defined by claim 10, wherein said active agent comprises capsaicin.

1 15.      A coated particle as defined by claim 10, wherein said active agent comprises a  
2           photodynamic therapeutic agent.

1 16.      A coated particle as defined by claim 10, wherein said active agent comprises a receptor  
2           protein.

1 17.      A coated particle as defined by claim 1, wherein said interior core comprises a reversed  
2           cubic phase material.

1 18.      A coated particle as defined by claim 17, wherein said interior core comprises an active  
2           agent disposed within said matrix.

1 19.      A coated particle as defined by claim 18, wherein said active agent comprises paclitaxel.

1 20.      A coated particle as defined by claim 18, wherein said active agent comprises capsaicin.

1 21.      A coated particle as defined by claim 18, wherein said active agent comprises a  
2           photodynamic therapeutic agent.

1 22.      A coated particle as defined by claim 18, wherein said active agent comprises a nucleic  
2           acid.

1 23.      A coated particle as defined by claim 18, wherein said active agent comprises a

1        glycolipid.

1 24.    A coated particle as defined by claim 18, wherein said active agent comprises an amino  
2        acid.

1 25.    A coated particle as defined by claim 18, wherein said active agent comprises a  
2        polypeptide.

1 26.    A coated particle as defined by claim 18, wherein said active agent comprises a protein.

2 27.    A coated particle as defined by claim 18, wherein said active agent comprises an  
3        antineoplastic therapeutic agent.

4 28.    A coated particle as defined by claim 18, wherein said active agent comprises an  
5        antihypertensive therapeutic agent.

6 29.    A coated particle as defined by claim 18, wherein said active agent comprises a rodent  
7        deterrent agent.

1 30.    A coated particle as defined by claim 18, wherein said active agent comprises a  
2        pheromone.

1 31.    A coated particle as defined by claim 18, wherein said active agent comprises a receptor  
2        protein.

1 32.    A coated particle as defined by claim 1, wherein said matrix comprises a material having  
2        the physicochemical properties of a biomembrane.

1 33.    A coated particle as defined by claim 32, wherein said biomembrane material comprises a  
2        biologically active polypeptide material.

1 34.    A coated particle as defined by claim 32, wherein said matrix comprises a polypeptide or

2 a protein immobilized in said biomembrane.

1 35. A coated particle as defined by claim 1, wherein said exterior coating comprises a  
2 nonlamellar crystalline material having a solubility of less than about 10 grams per liter  
3 of water.

1 36. A coated particle as defined by claim 1, wherein said exterior coating comprises a  
2 clathrate material.

1 37. A coated particle as defined by claim 1, wherein said exterior coating comprises an  
2 inclusion compound.

1 38. A coated particle as defined by claim 1, wherein said exterior coating comprises a zeolite  
2 material.

1 39. A method of making a coated particle comprising  
2 a. An interior core comprising a matrix consisting essentially of  
3 i. at least one nanostructured liquid phase,  
4 ii. at least one nanostructured liquid crystalline phase or  
5 iii. a combination of  
6 (1) at least one nanostructured liquid phase and  
7 (2) at least one nanostructured liquid crystalline phase and  
8 b. An exterior coating comprising a nonlamellar crystalline  
9 comprising

10 providing a volume of said matrix that includes at least one chemical species having a  
11 moiety capable of forming a nonlamellar crystalline material upon reaction with a second moiety  
12 and

13 contacting said volume with a fluid containing at least one chemical species having said  
14 second moiety to react said first moiety with said second moiety and contemporaneously  
15 subdividing said volume into particles by the application of energy to said volume.

1 40. A method of making a coated particle comprising

2        a.     An interior core comprising a matrix consisting essentially of  
3                    i.     at least one nanostructured liquid phase,  
4                    ii.    at least one nanostructured liquid crystalline phase or  
5                    iii.   a combination of  
6                        (1)    at least one nanostructured liquid phase and  
7                        (2)    at least one nanostructured liquid crystalline phase and  
8        b.     An exterior coating comprising a nonlamellar crystalline material  
9 comprising  
10        providing a volume of said matrix that includes said nonlamellar crystalline material  
11 dissolved therein and  
12        causing said nonlamellar crystalline material to become insoluble in said matrix and  
13 contemporaneously subdividing said volume into particles by the application of energy to said  
14 volume.

1 41.    A method of making a coated particle comprising  
2        a.     An interior core comprising a matrix consisting essentially of  
3                    i.     at least one nanostructured liquid phase,  
4                    ii.    at least one nanostructured liquid crystalline phase or  
5                    iii.   a combination of  
6                        (1)    at least one nanostructured liquid phase and  
7                        (2)    at least one nanostructured liquid crystalline phase and  
8        b.     An exterior coating comprising a nonlamellar crystalline material  
9 comprising  
10        providing a volume of said matrix that includes said nonlamellar crystalline material  
11 dissolved therein and that includes at least one chemical species having a moiety capable of  
12 forming said nonlamellar crystalline material upon reaction with a second moiety and  
13        contacting said volume with a fluid containing at least one chemical species having said  
14 second moiety to react said first moiety with said second moiety and contemporaneously causing  
15 said nonlamellar crystalline material to become insoluble in said matrix and subdividing said  
16 volume into particles by the application of energy to said volume.

1 42. A method of making a coated particle comprising  
2     a. An interior core comprising a matrix consisting essentially of  
3         i. at least one nanostructured liquid phase,  
4         ii. at least one nanostructured liquid crystalline phase or  
5         iii. a combination of  
6             (1) at least one nanostructured liquid phase and  
7             (2) at least one nanostructured liquid crystalline phase and  
8     b. An exterior coating comprising a first nonlamellar crystalline material  
9 and a second nonlamellar crystalline material comprising  
10         providing a volume of said matrix that includes said first nonlamellar crystalline material  
11 dissolved therein and that includes at least one chemical species having a moiety capable of  
12 forming said second nonlamellar crystalline material upon reaction with a second moiety and  
13         contacting said volume with a fluid containing at least one chemical species having said  
14 second moiety to react said first moiety with said second moiety and contemporaneously causing  
15 said first nonlamellar crystalline material to become insoluble in said matrix and subdividing  
16 said volume into particles by the application of energy to said volume.

1 43. A method of using a coated particle comprising  
2     a. An interior core comprising a matrix consisting essentially of  
3         i. at least one nanostructured liquid phase,  
4         ii. at least one nanostructured liquid crystalline phase or  
5         iii. a combination of  
6             (1) at least one nanostructured liquid phase and  
7             (2) at least one nanostructured liquid crystalline phase and  
8     b. An exterior coating comprising a nonlamellar crystalline material  
9 comprising  
10         disposing said particle in a fluid medium comprising an adsorbable material and  
11 adsorbing said adsorbable material on said exterior coating.

1 44. A method of using a coated particle comprising  
2     a. An interior core comprising a matrix consisting essentially of  
3         i. at least one nanostructured liquid phase,

- 1 ii. at least one nanostructured liquid crystalline phase or
- 2 iii. a combination of
  - 3 (1) at least one nanostructured liquid phase and
  - 4 (2) at least one nanostructured liquid crystalline phase and
- 5 b. An exterior coating comprising a nonlamellar crystalline material
- 6 comprising
  - 7 disposing said particle in a fluid medium comprising an absorbable material and
  - 8 absorbing said absorbable material in said interior core.
- 1 45. A method as defined in claim 44, wherein said absorbing is triggered by dissolution of
- 2 said exterior coating by said fluid medium.
- 1 46. A method as defined in claim 44, wherein said absorbing is triggered by disruption of
- 2 said exterior coating.
- 1 47. A method as defined by claim 44, wherein said absorbing occurs through pores in said
- 2 exterior coating.
- 1 48. A method of using a coated particle comprising
  - 2 a. An interior core comprising a matrix consisting essentially of
    - 3 i. at least one nanostructured liquid phase,
    - 4 ii. at least one nanostructured liquid crystalline phase or
    - 5 iii. a combination of
      - 6 (1) at least one nanostructured liquid phase and
      - 7 (2) at least one nanostructured liquid crystalline phase and
  - 8 b. An exterior coating comprising a nonlamellar crystalline material
  - 9 comprising
    - 10 disposing said particle in a fluid medium comprising an absorbable material and
    - 11 absorbing said absorbable material in said exterior coating.
- 1 49. A method of using a coated particle comprising
  - 2 a. An interior core comprising a matrix consisting essentially of

1                   i.        at least one nanostructured liquid phase,  
2                   ii.      at least one nanostructured liquid crystalline phase or  
3                   iii.     a combination of  
4                        (1)    at least one nanostructured liquid phase and  
5                       (2)    at least one nanostructured liquid crystalline phase and  
6                   b.      An exterior coating comprising a nonlamellar crystalline material  
7 comprising  
8                   disposing said particle in a fluid medium comprising an absorbable material and  
9                   absorbing said absorbable material in said interior core and exterior coating.

1 50.    A method of using a coated particle comprising  
2        a.     An interior core comprising a matrix consisting essentially of  
3           i.      at least one nanostructured liquid phase,  
4           ii.     at least one nanostructured liquid crystalline phase or  
5           iii.    a combination of  
6                (1)    at least one nanostructured liquid phase and  
7                (2)    at least one nanostructured liquid crystalline phase,  
8        said matrix comprising an active agent disposed therein, and  
9        b.     An exterior coating comprising a nonlamellar crystalline material  
10 comprising  
11       disposing said particle in a fluid medium and  
12       releasing said active agent into said fluid medium.

1 51.    A method as defined in claim 50, wherein said release is triggered by dissolution of said  
2        exterior coating by said fluid medium.

1 52.    A method as defined in claim 50, wherein said release is triggered by disruption of said  
2        exterior coating.

1 53.    A method as defined by claim 50, wherein said release occurs through pores in said  
2        exterior coating.

1 54. A method of using a coated particle comprising

2 a. An interior core comprising a matrix consisting essentially of

3 i. at least one nanostructured liquid phase,

4 ii. at least one nanostructured liquid crystalline phase or

5 iii. a combination of

6 (1) at least one nanostructured liquid phase and

7 (2) at least one nanostructured liquid crystalline phase and

8 said matrix comprising an active agent disposed therein,

9 b. An exterior coating comprising a nonlamellar crystalline material

10 comprising

11 releasing said active agent.

1 55. A method as defined in claim 54, wherein said release is triggered by dissolution of said

2 exterior coating by said fluid medium.

1 56. A method as defined in claim 54, wherein said release is triggered by disruption of said

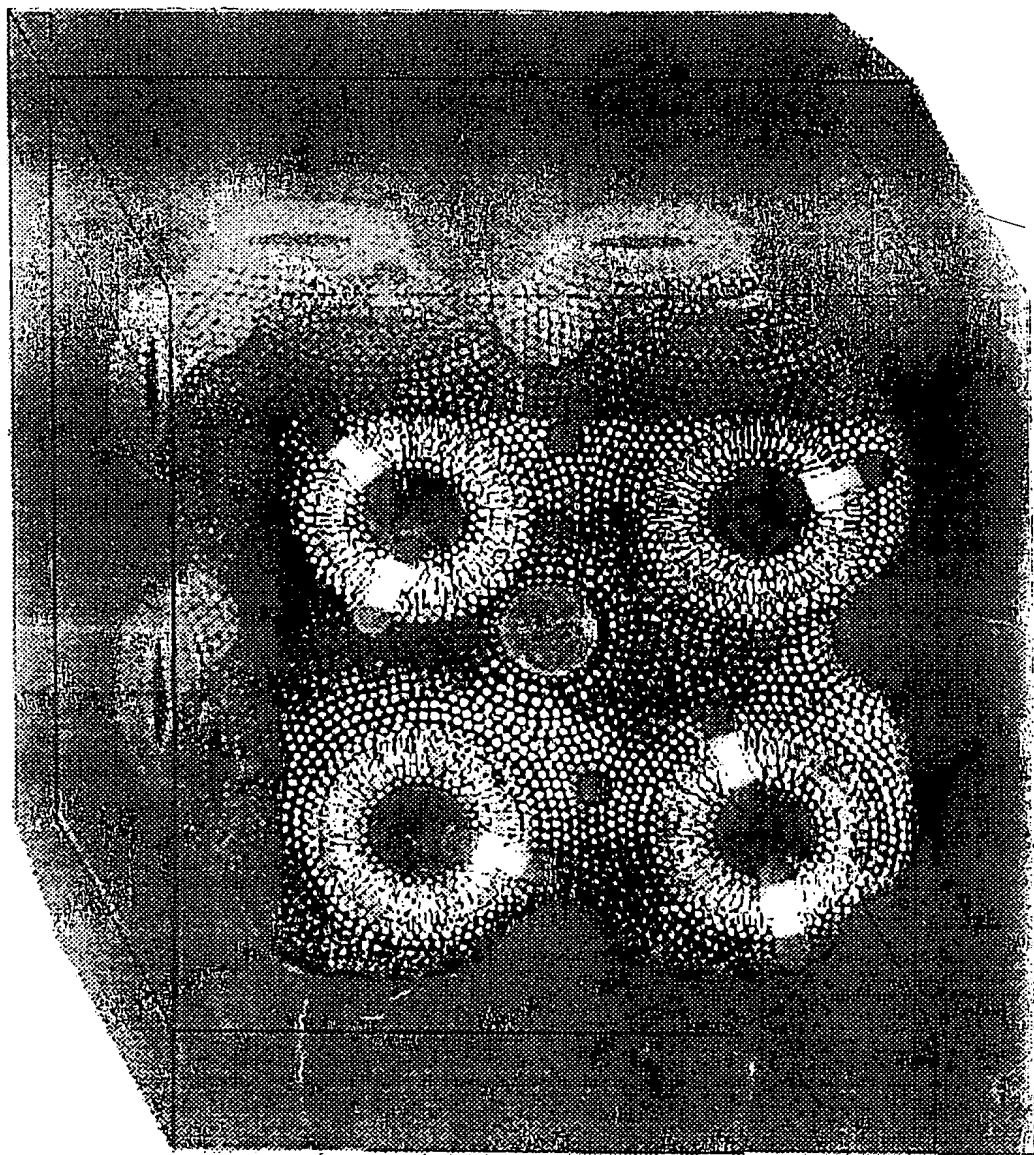
2 exterior coating.

1 57. A method as defined by claim 54, wherein said release occurs through pores in said

2 exterior coating.

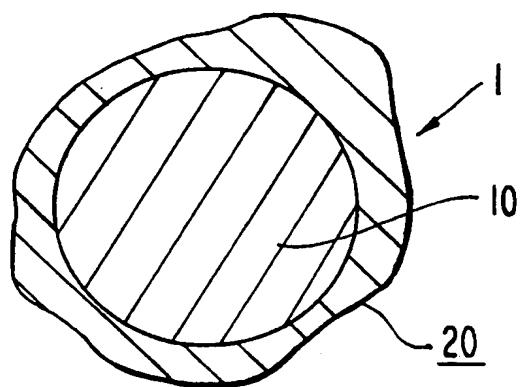
1/8

FIG. 1



SUBSTITUTE SHEET (RULE 26)

2/8



*FIG.2*

3/8

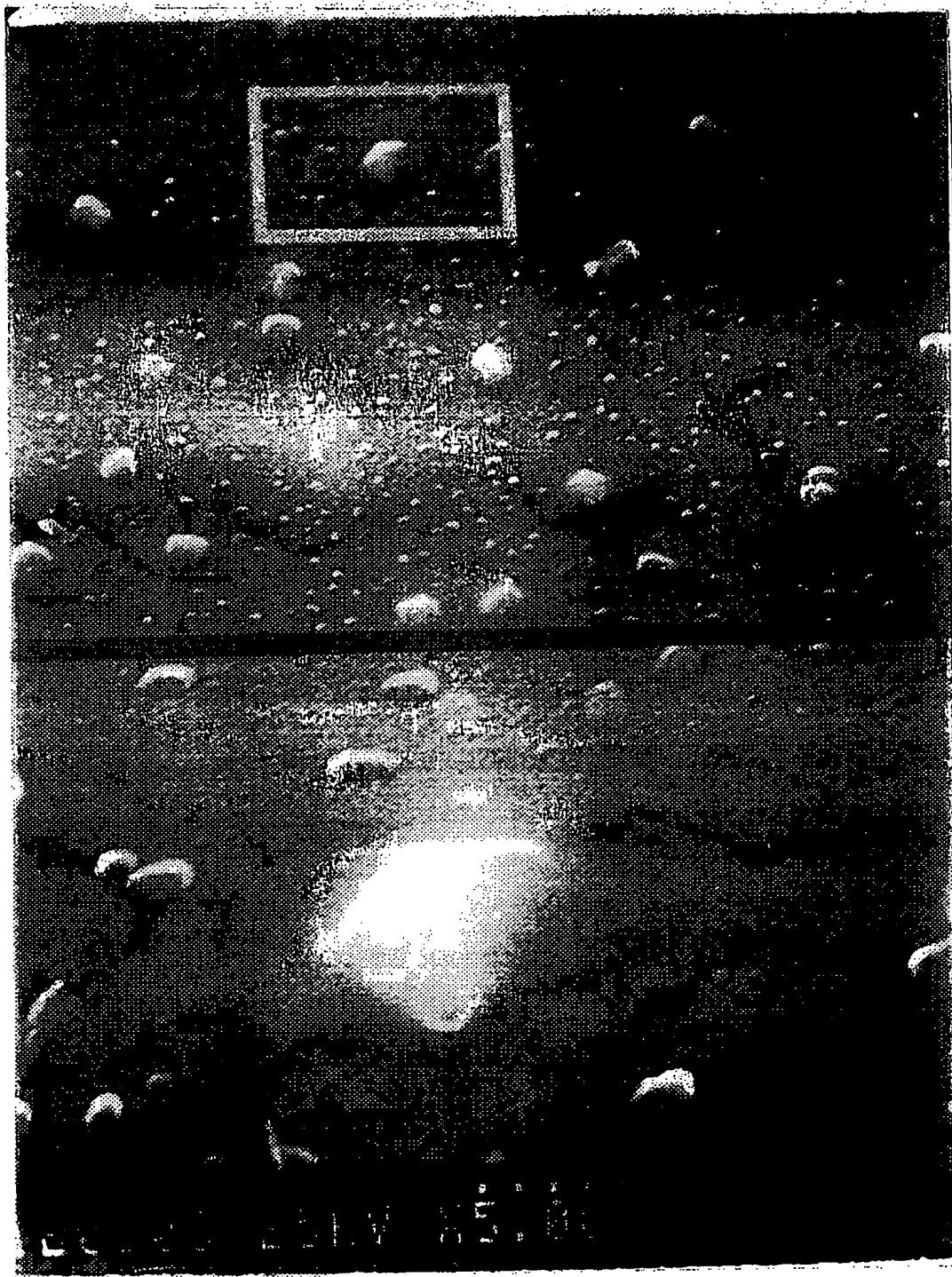
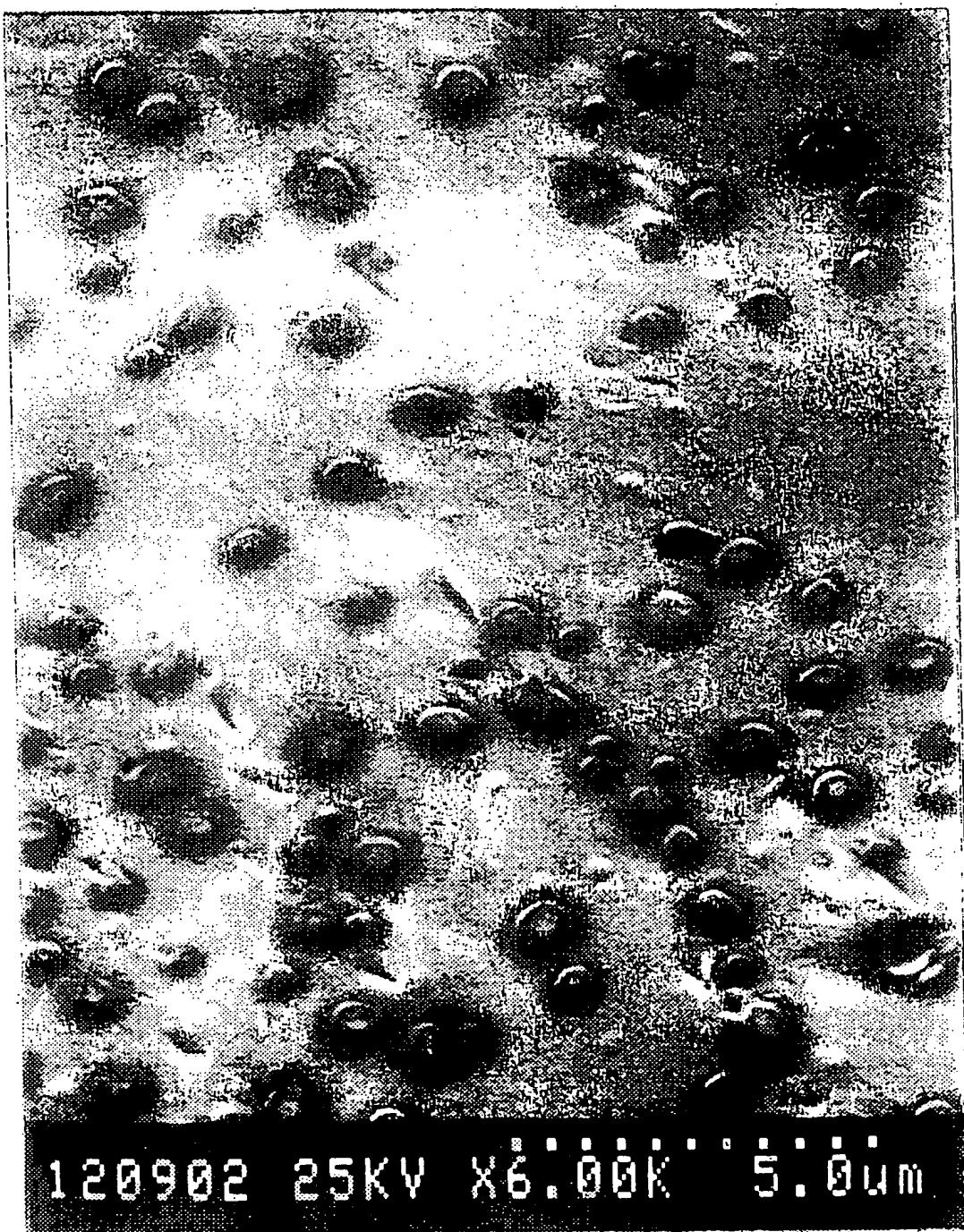


FIG.3

SUBSTITUTE SHEET (RULE 26)

4/8



*FIG. 4*

5/8

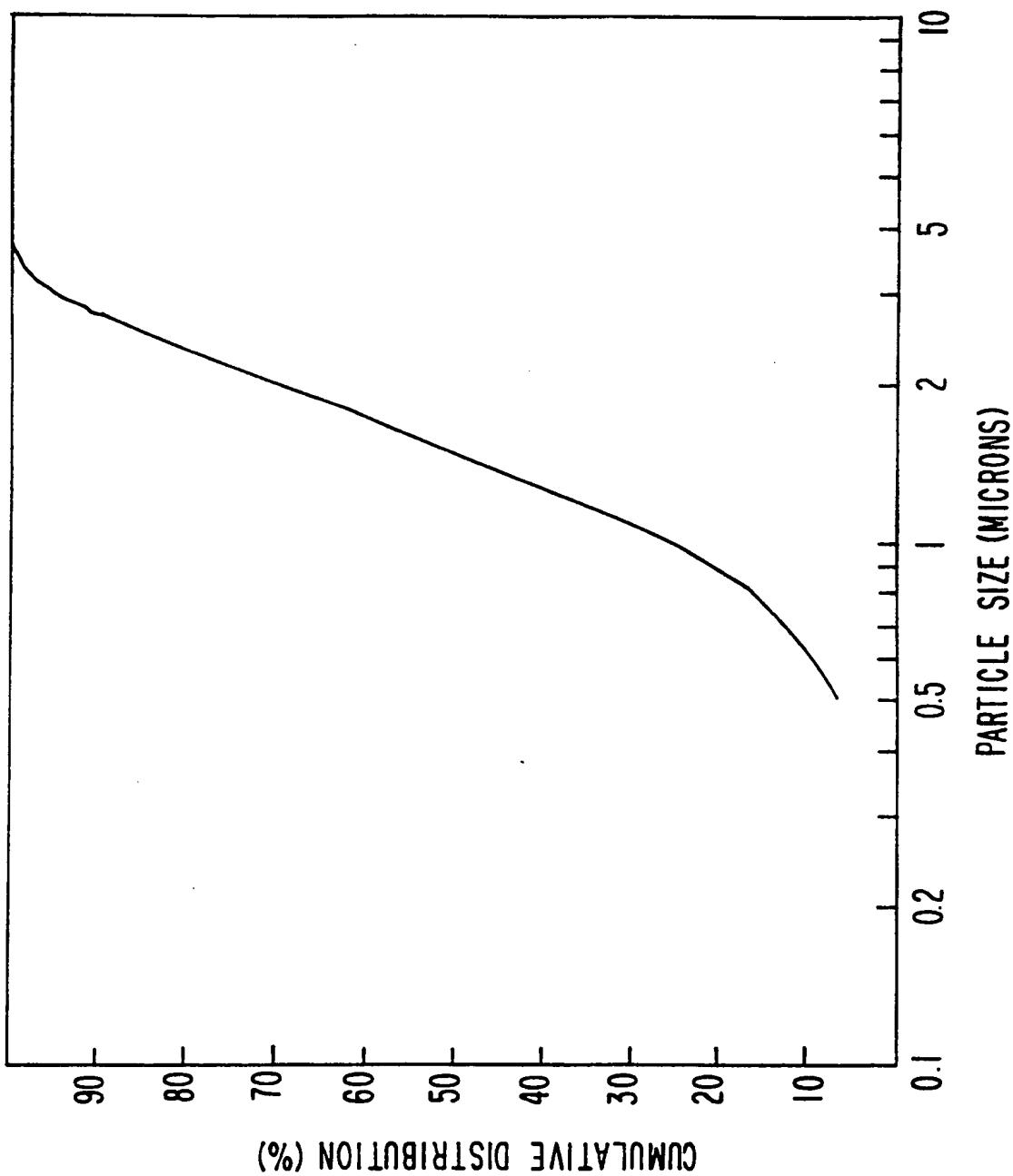
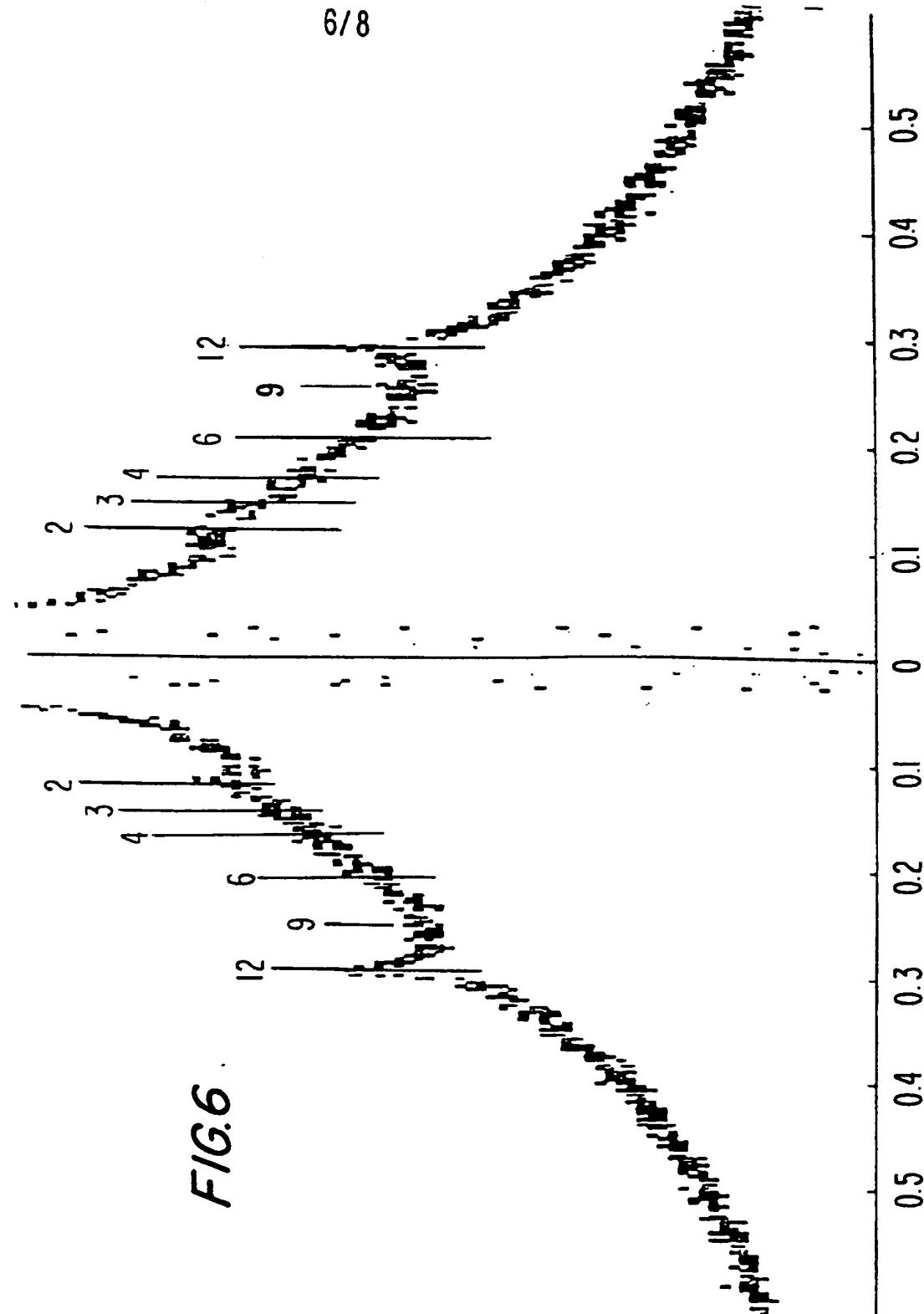


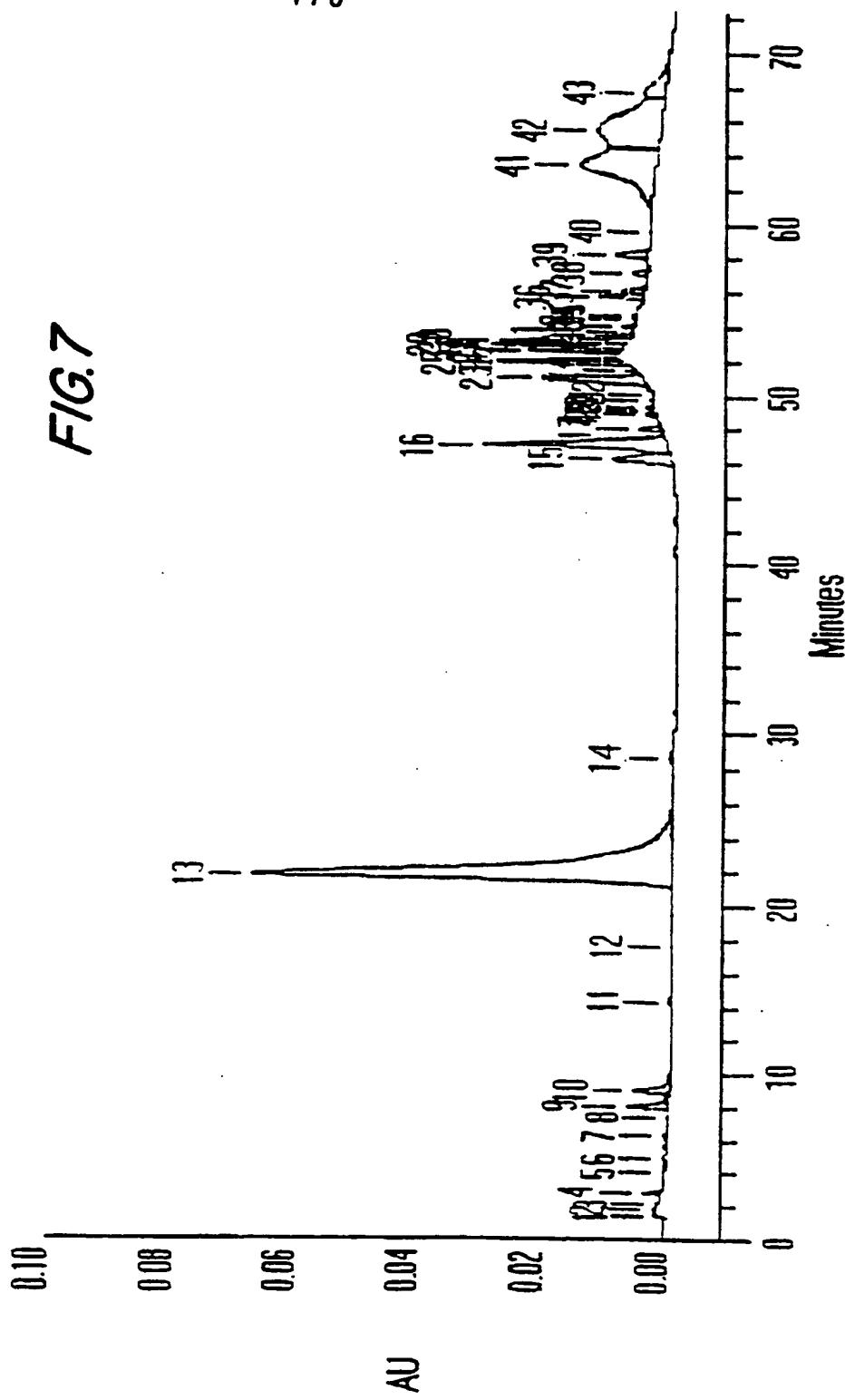
FIG. 5

6/8



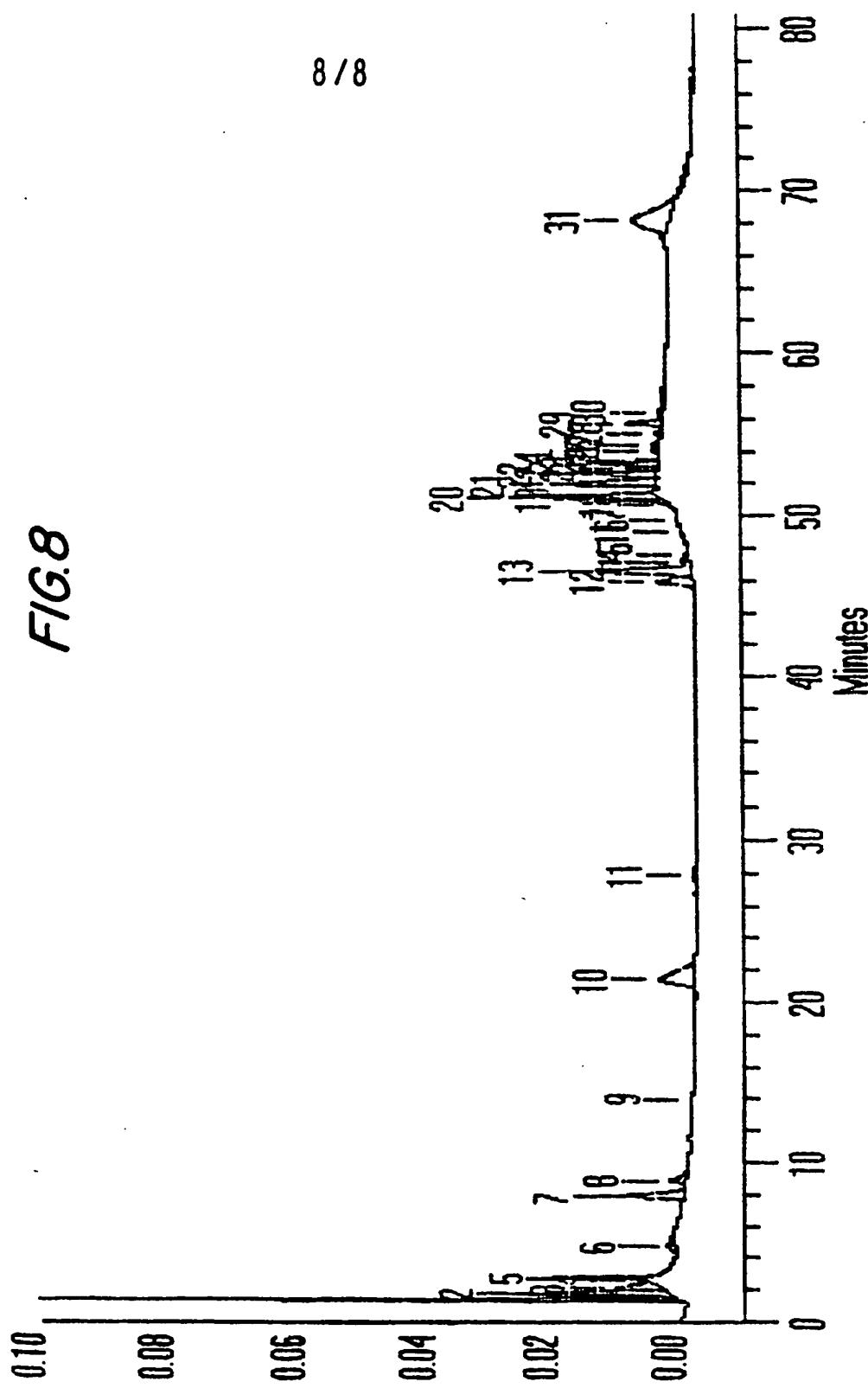
7/8

FIG. 7



8/8

FIG. 8



# INTERNATIONAL SEARCH REPORT

In. national application No.

PCT/US98/18639

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :Please See Extra Sheet.

US CL :Please See Extra Sheet.

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 264/4.1, 4.3, 4.33, 4.7; 427/2.14, 2.21, 213.3, 213.34, 213.36; 428/ 402.2, 402.21, 402.22, 402.24

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,344,857 A (SHASHA et al) 17 August 1982, see entire document.	1-57
A	US 5,039,559 A (SANG et al) 13 August 1991, see entire document.	1-57
A	US 5,407,609 A (TICE et al) 18 April 1995, see entire document.	1-57
A	US 5,543,158 A (GREF et al) 06 August 1996, see entire document.	1-57
A, P	US 5,679,377 A (BERNSTEIN et al) 21 October 1997, see entire document.	1-57
A, P	US 5,785,976 A (WESTESEN et al) 28 July 1998, see entire document.	1-57

Further documents are listed in the continuation of Box C.

See patent family annex.

•	Special categories of cited documents:		
"A"	document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"B"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"A"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

07 DECEMBER 1998

Date of mailing of the international search report

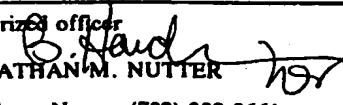
13 JAN 1999

Name and mailing address of the ISA/US  
Commissioner of Patents and Trademarks

Box PCT  
Washington, D.C. 20231

Facsimile No. (703) 305-3230

Authorized officer

  
NATHAN M. NUTTER

Telephone No. (703) 308-0661

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US98/18639

A. CLASSIFICATION OF SUBJECT MATTER:  
IPC (6):

B 01 J 13/02, 13/14, 13/16, 13/18; B32 B 9/02, 19/00, 19/02, 27/00

A. CLASSIFICATION OF SUBJECT MATTER:  
US CL :

264/4.1, 4.3, 4.33, 4.7; 427/2.14, 2.21, 213.3, 213.34, 213.36; 428/ 402.2, 402.21, 402.22, 402.24